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جامعة الإمارات العربيـة المتحدة
United Arab Emirates University

United Arab Emirates University

College of Engineering

Department of Civil and Environmental Engineering

SELECTION OF BEST SITES FOR AQUIFER STORAGE AND RECOVERY IN THE EASTERN DISTRICT OF ABU DHABI EMIRATE, UNITED ARAB EMIRATES

Karim Ali Mahfouz Abdou Khalil

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Water Resources

Under the Supervision of Prof. Mohamed Mostafa Ahmed Mohamed

May 2019

Declaration of Original Work

I, Karim Ali Mahfouz Abdou Khalil, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Selection of Best Sites for Aquifer Storage & Recovery in the Eastern District of Abu Dhabi Emirate, United Arab Emirates*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Mohamed Mostafa Ahmed Mohamed, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The Emirate of Abu Dhabi relied on groundwater as the main source of freshwater for several decades in the past. This resulted in the deterioration of the non-renewable groundwater aquifers; and thus, desalination plants have become the major source of freshwater supply in United Arab Emirates (UAE). Diminishing natural groundwater is a serious threat to freshwater security in arid regions. Because UAE has the world's highest per capita water consumption rate, more than 70 desalination plants have been built in the last two decades. A major concern, therefore, is the vulnerability of these desalination plants to pollution and emergency conditions. In emergency conditions, the maximum amount of stored water in reservoirs and distribution systems will be enough for only 48 hours. Currently, production of these plants exceeds national water demand and the surplus is used to recharge groundwater in specific locations. While production of desalination plants is constant, demand is continuously increasing and soon will exceed production and then new plants will be needed. This would require investments of billions of Dirhams; not to mention the effect of these plants on the environment. In other words, construction of new desalination plants cannot continue forever. The main aim of this thesis will be on increasing strategic water reserves in the Eastern District of Abu Dhabi through selecting the best locations for Aquifer Storage & Recovery (ASR). A limiting factor in applying ASR technology is the lack of suitable sites. Finding best locations for artificial recharge is one of crucial design steps. ASR technology offers an opportunity to store large volumes of water for later beneficial use. The artificial aquifer recharge with water for variety of applications has been successfully used worldwide. There are a range of methods used to recharge aquifers, including infiltration systems and injection wells. The choice of method depends on the type of aquifer, land area available and intended uses of the recovered water. Upon completion, this study would enhance water management in Al-Ain region to build a back-up reservoir to face potential threats of shortage in freshwater supply from desalination plants. Many hydrogeological factors need to be considered during the site selection process for ASR projects. These factors will be considered to assess the hydrological feasibility includes identifications of the best geological layers to receive the injected water. This work will provide a feasibility study of implementing managed aquifer recharge projects in Al-Ain region, to increase the

groundwater storage in suitable sites in Al-Ain region and modelling the groundwater aquifers and the feasibility to extract water from an aquifer to satisfy critical needs if a reserve had been established through implementation of an ASR program.

Keywords: Aquifer storage & recovery, groundwater, modelling, desalination, water security, hydrogeological, reservoirs, arid region, Abu Dhabi Emirate, Al-Ain region.

Title and Abstract (in Arabic)

اختيار أفضل المواقع لتخزين و استرداد المياه الجوفية في المنطقة الشرقية من إمارة أبوظبي، الإمارات العربية المتحدة

الملخص

اعتمدت إمارة أبوظبي على المياه الجوفية باعتبارها المصدر الرئيسي للمياه العذبة لعدة عقود في الماضي. وقد أدى ذلك إلى تدهور طبقات المياه الجوفية غير المتجددة؛ وبالتالي، أصبحت محطات تحلية المياه المصدر الرئيسي لإمدادات المياه العذبة في الإمارات العربية المتحدة. لأن الإمارات لديها أعلى معدل لاستهلاك المياه للفرد في العالم، فقد تم بناء أكثر من 70 محطة تحلية في العقدين الأخيرين. وبالتالي، فإن مصدر القلق كبير هو ضعف الاعتماد على هذه المحطات في حالة التلوث أو الظروف الطارئة حيث ستكون الكمية القصوى من المياه المخزنة في الخزانات وأنظمة التوزيع كافية لمدة 48 ساعة فقط. حاليا، يتجاوز إنتاج هذه المحطات الطلب على المياه الوطنية ويستخدم الفائض لإعادة شحن المياه الجوفية في مواقع محددة. في حين أن إنتاج محطات التحلية ثابت، فإن الطلب يزداد بشكل مستمر وسرعان ما سيتجاوز الإنتاج ومن ثم ستحتاج إلى مصانع جديدة وهذا يتطلب استثمارات مليارات الدراهم. ناهيك عن تأثير هذه المحطات على البيئة. وبعبارة أخرى، فإن بناء محطات تحلية جديدة لا يمكن أن يستمر إلى الأبد. الهدف الرئيسي لهذه الرسالة هو زيادة احتياطي المياه الاستراتيجي في المنطقة الشرقية من إمارة أبوظبي من خلال اختيار أفضل المواقع لتخزين المياه تحت سطح الارض بداخل الخزانات الجوفية. العامل المحدد في تطبيق تكنولوجيا تخزين واسترداد المياه من الخزانات الجوفية هو نقص المواقع المناسبة حيث يعتبر العثور على أفضل المواقع لإعادة التغذية الاصطناعية إحدى خطوات التصميم الهامة. توفر تقنية التخزين والاسترداد للمياه تحت سطح الارض (ASR) فرصة لتخزين كميات كبيرة من المياه للاستفادة منها لاحقًا وقد تم استخدام طريقة تخزين المياه في طبقة المياه الجوفية الاصطناعية التي يتم إعادة شحنها بالمياه لتطبيقات متنوعة بنجاح في جميع أنحاء العالم. هناك مجموعة من الطرق المستخدمة لإعادة شحن طبقات المياه الجوفية، بما في ذلك آبار الحقن بالمياه ويعتمد اختيار الطريقة على نوع طبقة المياه الجوفية، ومساحة الأرض المتاحة والاستخدامات المقصودة للمياه المسترجعة.

عند الانتهاء، ستعزز هذه الدراسة إدارة المياه في منطقة العين لبناء خزان احتياطي لمواجهة التهديدات المحتملة للنقص في إمدادات المياه العذبة من محطات التحلية. هناك حاجة

للنظر في العديد من العوامل الهيدروجيولوجية خلال عملية اختيار الموقع لمشاريع ASR. سوف يتم النظر في هذه العوامل لتقييم الجدوى الهيدرولوجية وتشمل تحديد أفضل الطبقات الجيولوجية لتلقي المياه المحقونة. سيوفر هذا العمل دراسة جدوى حول تنفيذ مشاريع التغذية الجوفية المدارة في منطقة العين، لزيادة تخزين المياه الجوفية في المواقع المناسبة، ونمذجة المياه الجوفية وجودة استخراج المياه من طبقة المياه الجوفية لتلبية الاحتياجات الحرجة، إذا تم إنشاء احتياطي من خلال تنفيذ برنامج ASR.

مفاهيم البحث الرئيسية: تخزين واسترداد المياه الجوفية، المياه الجوفية، تحلية المياه، الأمن المائي، الهيدروجيولوجي، الخزانات، المنطقة القاحلة، إمارة أبوظبي، منطقة العين.

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Dedication

To my beloved parents and family

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List of Abbreviations

ACES	Arab Center for Engineering Studies
ASR	Aquifer Storage & Recovery
ASTR	Aquifer Storage Transfer & Recovery
EAD	Environment Agency – Abu Dhabi
GCC	Gulf Cooperation Council
MAR	Managed Aquifer Recovery
MCM	Million Cubic Meter
MGD	Million Gallon per Day
MIG	Million Imperial Gallon
NCM	National Center of Meteorology
NDC	National Drilling Company
PPM	Part Per Million
SCAD	Statistics Center of Abu Dhabi
TDS	Total Dissolved Solids
TRANSCO	Abu Dhabi Transmission & Despatch Company
TSE	Treated Sewage Effluent
UAE	United Arab Emirates
VMOD	Visual MODFLOW Flex

Chapter 1 : Introduction

1.1 Overview

The Eastern District of Abu Dhabi Emirate is characterized by the limited natural water resources which is represented by Groundwater only. The scarcity of rainfall and high evaporation rates led the emirate to rely on the desalinated water, the natural groundwater and limited rely on treated wastewater. The high rates of groundwater withdrawals for vegetation and farming purposes led to significant decline in the groundwater levels which is estimated more than - 15 m and quality exceeded 100,000 ppm at some areas in Al-Ain region (EAD, 2017a). For example, Al-Khazna-Remah area within Al-Ain region produce water by several farm wells at rates exceeding 150 m^3/hr (EAD, 2011a). The desalination plants have a great role to fulfil the water demand with desalinated water that accounts for 29% of the total water consumed in the emirates. The desalination capacity has increased significantly over the last decade and demand is quickly overtaking the supply. Therefore, there should be a management strategy to overcome this expected shortfall. Aquifer storage and recovery (ASR), which is referred to the injection of desalinated water into strategic underground aquifers for future use, is considered to be one of the important solution to overcome the increasing water demands.

1.2 Statement of the Problem

Desalination plants are threatened by contamination from unpredicted environmental disasters of other crises. The small capacity of desalinated water stored near the desalination plants (Ground Storage Tanks) is used during the maintenance-forced short shutdowns of the desalination plants. It has been reported by some large-scale desalination plants managers that the distribution system storage capacities range from only few hours to few days. During some climatic conditions, such as the cyclone that struck the Sultanate of Oman in 2006, or pollution events such as red tide or oil spill such as the oil spill occurred in Sharjah, some desalination plants were forced to shut down for few days. These shut-downs caused the water service to be cut in several areas due to a deficiency in storage tank capacity (Missimer et al., 2012). It may have been feasible to extract water from an aquifer to satisfy critical needs if a reserve had been established through the implementation of an ASR program.

1.3 Relevant Literature

The desalination plants, shown in Figure 1, have been established to cover the shortages of conventional water resources and to meet the high demand of water for domestic, agricultural and industrial purposes. In addition, treated effluents from wastewater treatment plants are used to reduce groundwater production and the costly production of desalinated water. Significant efforts were started to the assessment and management of water resources such as implementation of sustainable water resources strategy in order to augment the groundwater storage and cope with increasing demand.

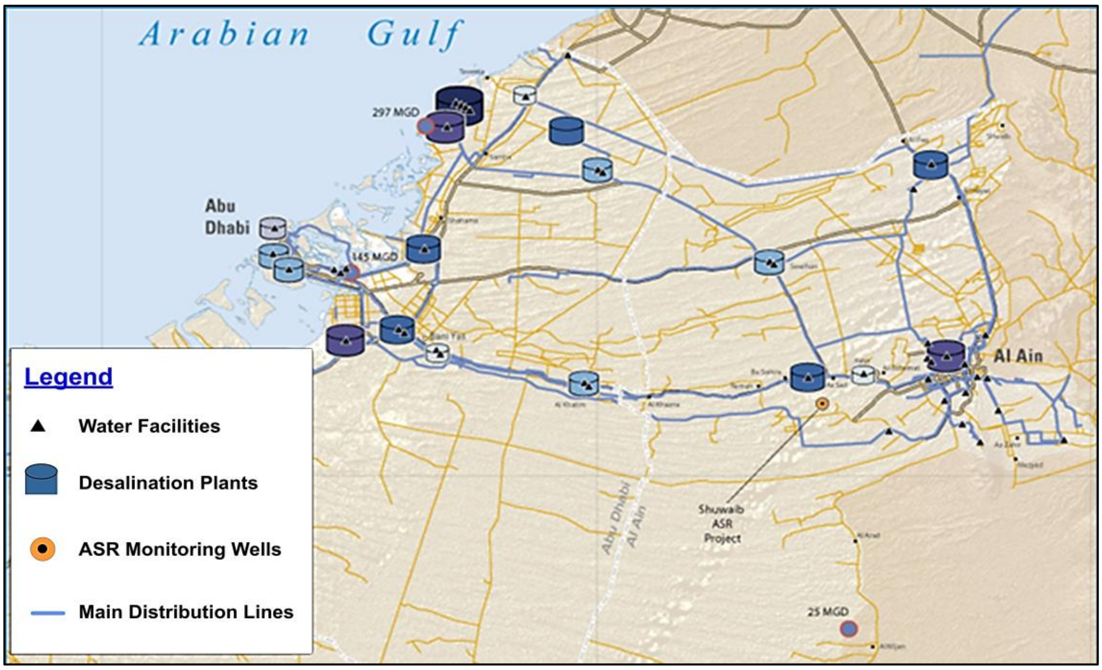


Figure 1: Water infrastructure in UAE (EAD, 2011b)

All the Desalination Plants are located in Dubai, Fujairah and Abu Dhabi Emirates near to the shoreline (Arabian Gulf) to desalinate the seawater and distribute it through pipelines to the remote water facilities. Al-Ain region depends on Taweela and Umm Al-Nar desalination plants to fulfil its water demand.

Groundwater augmentation has been hotly debated for a number of years and the choices favored are using treated sewage effluent (TSE) and excess desalinated water to recharge the groundwater reservoir. Besides, the construction of detention or recharge dams in the major Wadi catchments of the region.

1.3.1 Groundwater in UAE

UAE is located within the arid zone in the southeastern part of Arabian Peninsula. The arid zone is characterized by low amount of rainfall and high levels of evaporation (Rizk and Alsharhan, 2003). The groundwater is found in all regions of the UAE, and its potential quantity and quality in any area depends mainly on the geological formations prevailing in that region, where areas of gravel flats and oases in the country are with high potential of water, but as a result of pumping operations continued substantially over previous years with limited rates of natural feeding, severe depletion of the groundwater has been developed in certain areas of the country (Murad, 2010), where the most important negative phenomena related is the underground desertification, due to depletion of the groundwater depth and increase in the concentration of salts in water and as a result of seawater intrusion in coastal areas or overlap with the salted water of some geological formations deep. This has a direct impact on agricultural activity and low productivity of agricultural land (Dawoud and Sallam, 2012), and more important is the decrease in strategic reserves of freshwater in general.

Groundwater's consumption has increased dramatically during the last two decades and it was reported by EAD (2017a), that 2,013 Mm^3 groundwater abstracted in 2015, partly as a result of population growth and rapid economic. Furthermore, the desalination capacity has increased significantly to around 800 million gallon per day (MGD) in 2010 compared to 200 million gallon per day in 1998 which reflect the increase in water demand as presented in Figure 2. For example, the population of the Abu Dhabi Emirate has increased significantly to be 2,908,173 persons in mid-year 2016 compared to around 211,812 persons in the 1975 according to SCAD (2018). The other main cause is the expansion of the irrigated agricultural lands as the size of arable land expanded from 22.377 km^2 to 749.868 km^2 from the period 1971 to 2017 according to SCAD (2018). Where agricultural sector is considered the major consumer of groundwater, agriculture accounts for 76% of the groundwater, 23% for forestry, and 1% for domestic, amenity, and industrial sectors (Dawoud and Sallam, 2012). The annual groundwater recharge in the UAE is estimated at 120 million m^3/year (Almulla, 2005), while the groundwater abstraction is estimated at 2,013 million m^3/year in 2015.

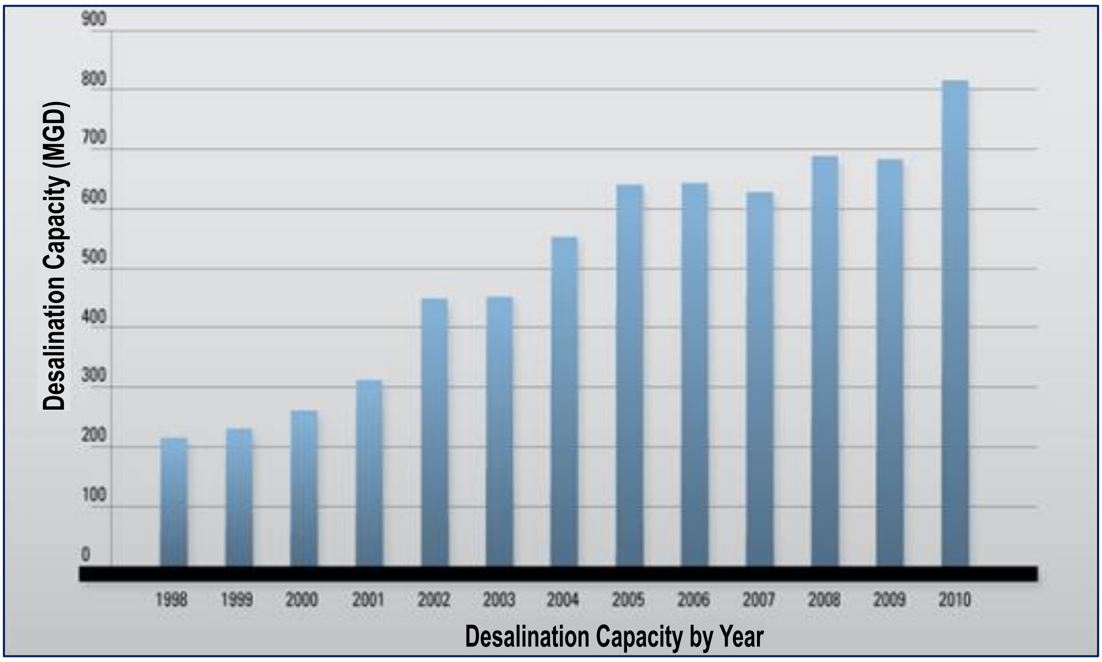


Figure 2: Desalination capacity (MGD) by year (EAD, 2011b)

1.3.2 General Review on MAR

Management of aquifer recharge (MAR) is also called sustainable underground storage and it is gaining a lot of considerations for water managers all over the world due to it provides a cheap technique than the other storage techniques and economic solution of a safe water supply. The MAR is considered to have the potential to be a major supplier for water in semi-arid and arid countries where groundwater is over-exploited or saline. The successful implementation of MAR will depend on understanding of the capabilities and constraints of the MAR techniques and the existing water infrastructure (Dillon, 2005). Figure 3 presents the various techniques of MAR.

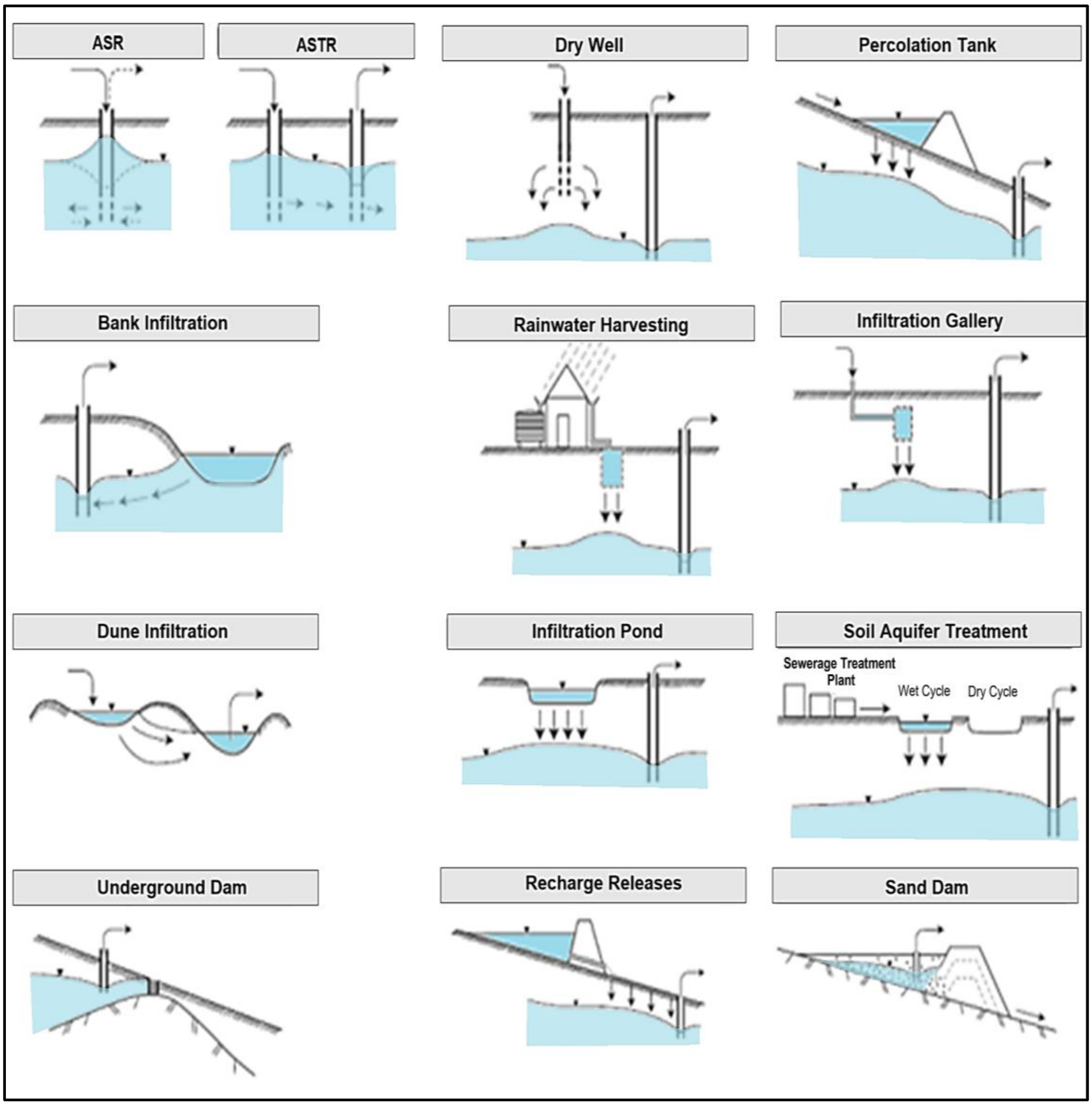


Figure 3: Schematic of types of MAR (adapted from Dillon, (2005))

MAR ‘managed aquifer recharge’ depends mainly on the local hydrology and will play an important role in solving water scarcity and restore the groundwater. One of the improvements in implementing the MAR systems are the conventional and advanced technologies applications to improve the aquifer characterization that will help in understanding of the local hydrogeological settings while the main challenge in studying the MAR system performance is the groundwater modelling which require a comprehensive conceptual model and data on aquifer (Maliva et al., 2015).

1.3.3 MAR in GCC

The increasing population in Gulf Cooperative Council (GCC) Countries and the global warming will result in water scarcity in the future and the situation will be worsen in the countries that doesn’t develop large storage capacities of water to meet domestic, industrial and agricultural demands. An effective water management solution for the available water resources is required to overcome the expected water scarcity problem and to meet critical need for strategic long-term storage (Missimer et al., 2012). The MAR techniques are currently applied in many countries (Dawoud, 2014) as a solution to satisfy long term needs and emergency circumstances.

Hutchinson (1998), Al-Noaimi et al. (2012), and Klingbeil (2012) listed some Gulf countries implementing MAR technology, the country and its MAR technique is listed below.

- Bahrain (Isa town: storm water runoff): Unique gravity fed aquifer recharge systems via gulley’s, catch-pits, delivery pipes, oil trap, filter chamber, and recharge well (estimated recharge volume is 1,389 m^3) as well as a potential larger scale ASR/ASTR storing treated sewage effluent (TSE) in Dammam and Khober Aquifers (Al-Noaimi et al., 2012). The future TSE productions in 2030 is expected to be 500,000 m^3/day and aims to direct TSE reuse in agriculture (Klingbeil, 2012).
- Kuwait (Dammam, Kuwait Group): surplus of desalinated water produced during the winter season encouraged groundwater authorities in Kuwait to evaluate the potential artificial groundwater recharge (Hutchinson, 1998). In 1992, injection of desalinated water into Dammam Limestone and Kuwait group. In 2010, selection of suitable sites for artificial recharge (Kuwait group: Multa, Sulabiya, Rawadatain areas and Dammam Formation: Kabd area).

- Oman (Groundwater Recharge Dams): More than 30 groundwater recharge dams, intercepting wadi runoff, allowing for controlled recharge downstream of dam. Managed to hold about million cubic meters (MCM) of flood waters until end of 2009 (Klingbeil, 2012).
- Qatar (Northern Groundwater Basin, ASR): in 1976, artificial recharge with desalinated seawater to allow an agricultural expansion, control of saltwater intrusion and developing a strategic reserves appears technically feasible but its practicability needs to be examined. During 1992-1994: feasibility study for injection of desalinated water in Rus Formation and Umm Er-Radhuma Formation, results were positive for both Formations. In 2012: QNFSP/KAHRAMAA investigated four sites in northern groundwater basin for storage of 136 MCM as a long term security to overcome any crises conditions or interruption to desalination plants.

1.3.4 MAR in UAE

Abu Dhabi city is listed amongst the highest water per capita consumers (590 Liter per day) according to EAD (2017a) and the challenges to maintain a sustainable water supply are several such as surface water which is almost absent due to the scarcity of rainfall and the high evaporation levels as well as groundwater are the only conventional water resources in the country (Al-Katheeri, 2008).

According to SCAD (2018), a large portion of the water demand is provided by desalinated water with consumption estimated around 1,295.5 MCM in 2017 produced by coastal desalination plants desalination plants in Abu Dhabi Emirate (SCAD, 2018). This portion is estimated around 35% from the total water consumption in Abu Dhabi Emirate according to EAD (2016a). In the Abu Dhabi Emirates, 71.3%

of the water is consumed in agriculture, foresting and landscaping which is estimated by more than 2,000 cubic meter per year, 16.5% of the water is consumed by domestic sector, 4.7% for governmental sector, 6.5% for commercial sector, 0.8% for industrial sector and 0.1 for other sectors (EAD, 2017a).

The need for an alternative approach to manage the water supply demand and provide uninterrupted freshwater supply is a major concern in the Abu Dhabi Emirate. This approach would overcome any interruptions in the water supply caused by emergencies and the minimum 1 year time needed required to construct a new desalination plant (Al-Katheeri, 2008).

Abu Dhabi Emirate is in need of a large storage system that will overcome demand during peak periods, emergencies and periods when desalination plants are out of commission for such reasons as natural disasters, industrial accidents, war, oil spill and other crises. The excess freshwater from desalination plants could be stored in aquifers using artificial recharge techniques which is one of the managed aquifer recharge techniques (Dillon, 2005; Al-Katheeri, 2008; Maliva et al., 2009b; Missimer et al., 2012). One method to achieve this strategic water reserve is artificial storage and recharge 'ASR' by injecting the aquifers with the excess freshwater produced by the desalination plants or any other type of water.

Three ASR pilot projects of artificial recharge have been planned in the UAE, the first operational ASR in Nizwa, Sharjah, one in the western region 'Liwa' and the other one in Al-Ain region (Hutchinson, 1998; Al-Katheeri, 2008; Klingbeil, 2012; Dawoud, 2014).

- Nizwa Area, Sharjah Emirate

Considered as the first operational ASR system to establish a cost effective storage of freshwater produced from desalination plant during the low demand periods (Sharjah Electricity & Water Authority, 2009). A feasibility study started on 2003-2005, followed by pilot testing of the ASR project from 2006-2009. The aim of the ASR is to replace the seasonal peak load capacity and utilize it during the high demand periods. Based on the results of the pilot testing and numerical models, the recovery efficiency of the injected water is 95% with high potentiality to implement the ASR system.

- Liwa Area, Abu Dhabi Emirate

Large scale strategic water storage and recovery project aimed to store a surplus of 23 MCM desalinated seawater (approximately 64,000 m^3/day) produced during low water for emergency water supply for Abu Dhabi Emirate up to three months. The surplus desalinated water was injected in a shallow to moderately deep aquifer north of Liwa area.

- Al-Ain Region, Abu Dhabi Emirate

The project was undertaken by National Drilling Company (NDC) in Al-Ain in 1998. Excess water from Umm Alnar and Taweela desalination plants was stored in shallow aquifer. The results of the study indicate that ASR is important approach for restoring the depleted aquifer (Al-Katheeri, 2008).

There are two scenarios allow the construction of ASR pilot projects in Al-Ain city. The first scenario is to locate the ASR system near to the desalinated water pipelines which will recharge the aquifer when there is surplus in the desalinated water during the winter/low demand periods. The second scenario is based on recharging the surficial aquifers that has been investigated by NDC as they obtain a large database of wells in Al-Ain region.

1.3.5 Water Storage Capacity in the GCC Countries

The scarcity of water resources in the Gulf Corporation Council (GCC) countries is considered a major problem that represent potential water risk. The Gulf countries rely mainly on desalination plants which are subjected to interruptions in the water production due to several unexpected circumstances such as wars, contaminations, oil spills, equipment breakdown, and climatic events (Almulla et al., 2005; Missimer et al., 2012).

Many regions such as Al-Ain region that are located away from the coastline (approximately greater than 150 km from the Arabian Gulf) where the desalination plants are located rely mainly on the freshwater produced by those plants. There are long pipelines (main distribution lines) connecting the desalination plants with the water facilities located at different areas within Al-Ain region as presented in Figure 4. In the event that emergency situation, damaged, maintenance or serious disruptions occurred, the remote city/region will be left without freshwater supply for an unspecified time period (Missimer et al., 2012).

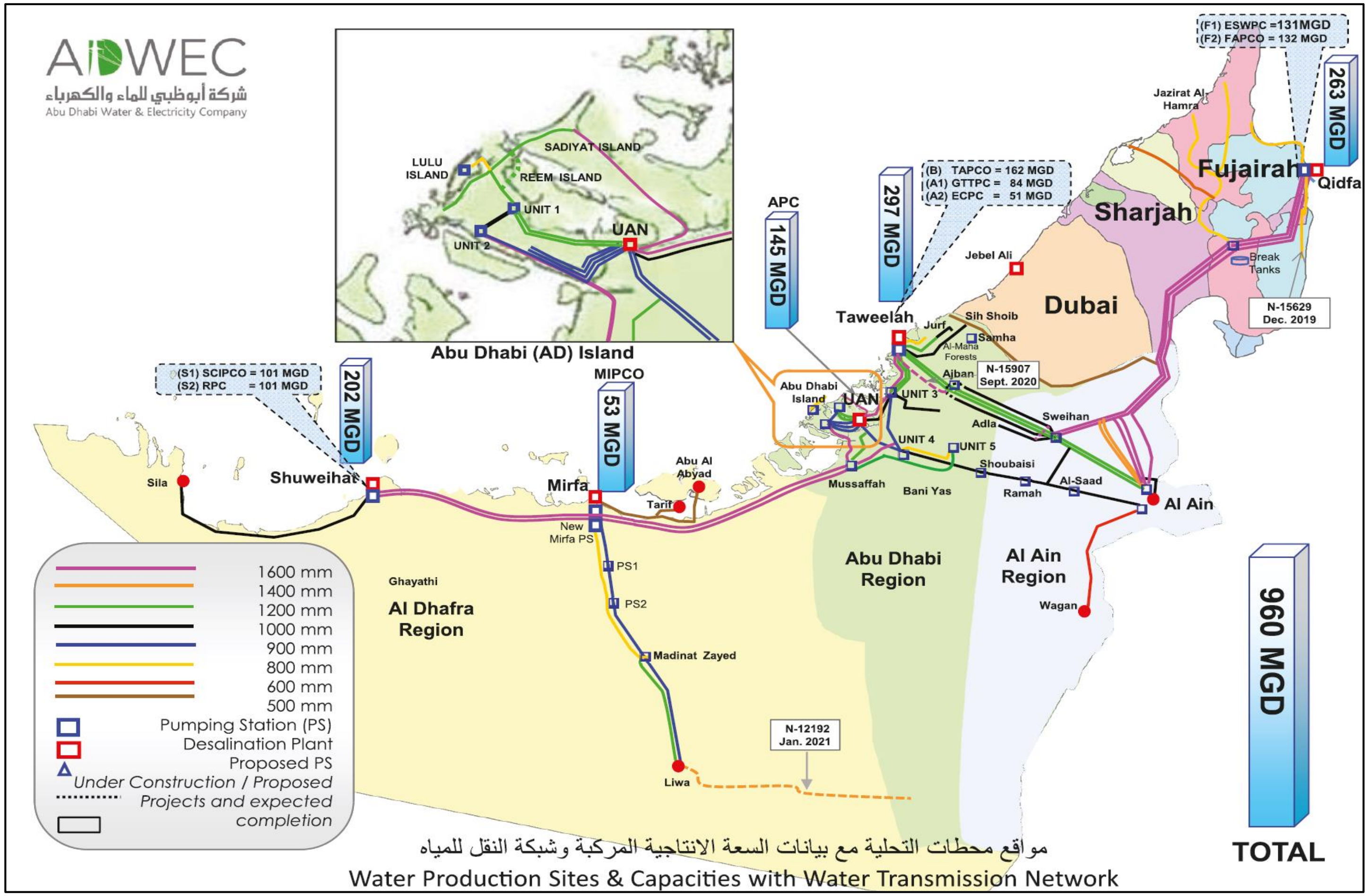


Figure 4: Water system network in UAE (ADWEC, 2017)

In GCC countries, the water stored in ground storage tanks and distribution network is sufficient for one day only (Almulla et al., 2005; Dawoud, 2014). Kuwait and Kingdom of Saudi Arabia (K.S.A) has the highest number of days of water storage among the other GCC countries while other countries such as UAE and Qatar just have 2 days water storage as presented in Figure 5 which is considered very low and not enough to supply the demand in case of any emergency circumstances.

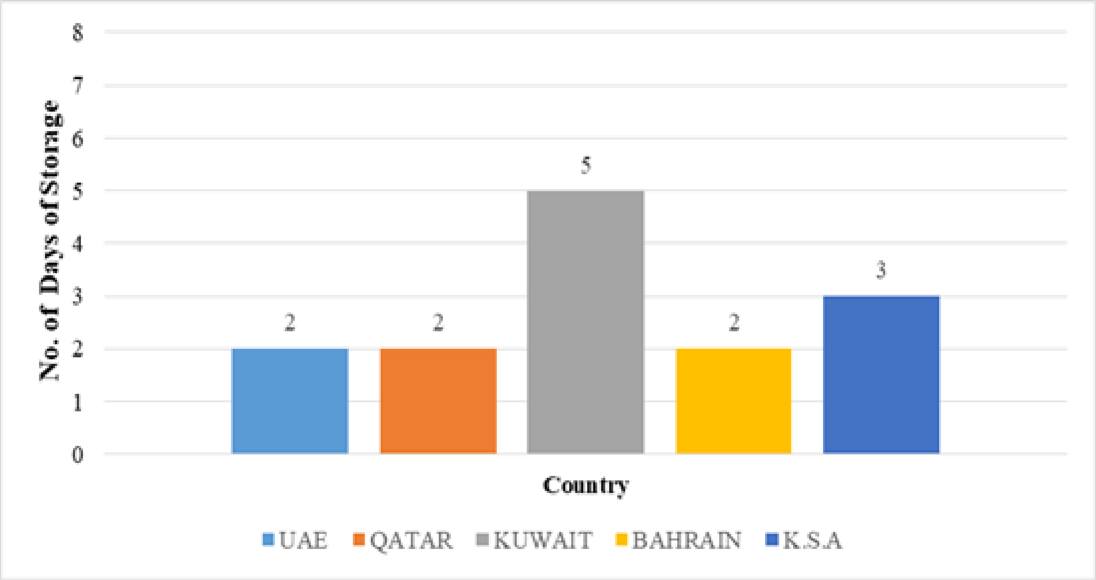


Figure 5: Maximum water storage of GCC countries (adapted from Dawoud (2014))

Therefore, it is necessary to find a new managerial approaches to provide uninterrupted water supply and to overcome any unpredicted or emergency situations. A common strategic water security solution is Aquifer Storage and Recovery (ASR) that can play a significant role in the UAE and GCC countries.

The ASR technique will provide uninterrupted freshwater supply during emergencies (natural disasters, industrial accidents, war, contaminations, oil spill, earthquake and other crisis) as well as it will serve as a strategic water reservoir. Al-Ain region needs to have a long-term storage capacity.

Chapter 2 : Aquifer Storage and Recovery

Aquifer Storage and Recovery (ASR) is a water storage and treatment technology that has developed and started in the United States since 1968 when the first ASR system began operation at wildwood, New Jersey. ASR through wells is specific type of feasible and cost-effective technique for storing water underground through one or more wells during times when surplus water is available and is recovered from the same well/wells later times to meet the demand of urban, agricultural, ecosystem, industrial, recreational, seasonal and long-term, emergency, or other demands (Pyne, 1995; Pyne and Howard, 2004; Izbicki et al., 2010; Rambags et al., 2013; Dawoud, 2014). The same well can be used for injecting and recovery as presented in Figure 6.

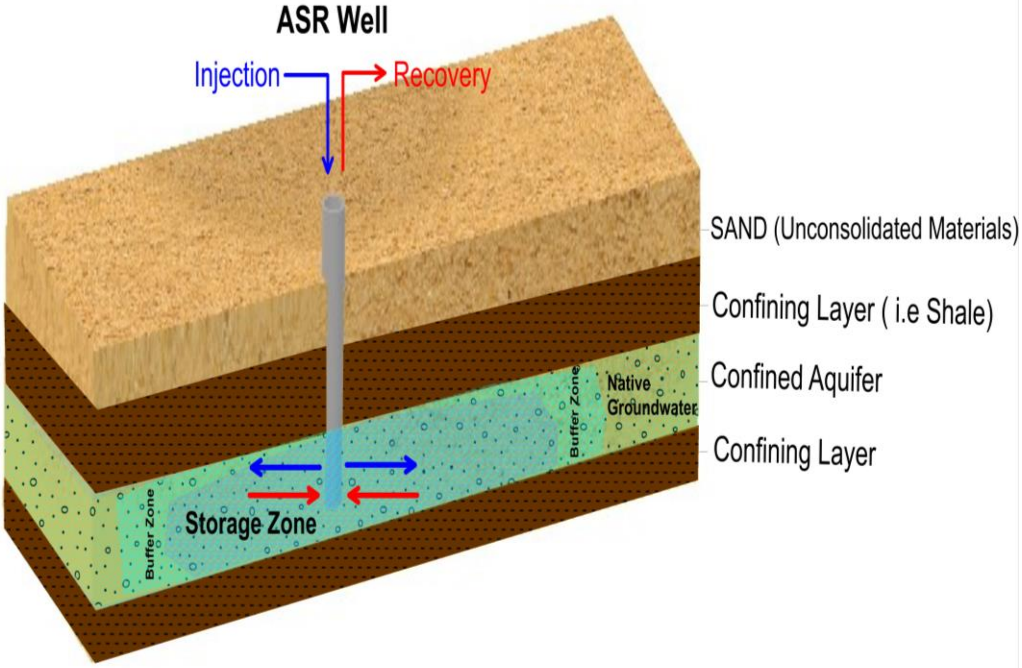


Figure 6: Sketch of the ASR system

ASR is a common technique that attracted the attention to many countries due to the advances in geological science and engineering in storing water underground (Maliva et al., 2015) rather than applying the well-known storage techniques; normal tanks which is most expensive and lined ponds which require huge area of land (Almulla et al., 2005; Rambags et al., 2013).

The largest ASR well field is located in Las Vegas, Nevada, United States and has over than 500 million liter per day of recovery capacity (Pyne and Howard, 2004). The ASR is favored by many countries because there are insignificant evaporation losses (Maliva et al., 2011) and the stored water is not vulnerable to contamination by animals or humans if well designed. ASR system can be used to store any type of water (Sheng, 2005; Missimer and Maliva, 2010a; Izbicki et al., 2010; Klingbeil, 2012; Dawoud, 2013), examples include:

- Potable Water System

In winter, there is a surplus in the freshwater produced from the desalination plants and can be stored to be used during high demands periods or in emergency situations by pumping out the freshwater and use it.

- Reclaimed Wastewater System

In UAE, treated wastewater is utilized for irrigation and plantations purposes (Brook and Dawoud, 2005). However, in winter there is a huge surplus in treated wastewater comparing to the summer where there is a shortage in irrigation water.

- Storm Water System

Rainwater can be collected in Dams and directed to water storage facilities.

2.1 ASR in UAE

The implementation of ASR systems in UAE is a potential solution to a problem facing water managers in the country. Abu Dhabi Emirate has studied the possibility of storing huge quantities of surplus desalinated seawater into the underground by storing the water into an existing fresh groundwater aquifer at Liwa area (GTZ, 2002).

In Al-Ain region, the first pilot project was launched by National Drilling Company (NDC) in Al-Ain region in 1998 where surplus desalinated water from Umm Al-Nar and Taweelah desalination plants is stored subsurface in the surficial aquifer system for future recovery during high demands (Hutchinson, 1998). The aim of the study was to assess the feasibility of augmentation and revitalizing the critical groundwater resources of Al-Ain region. The results of the study indicates that the aquifer storage recovery is a feasible alternative for enhancing the depleted aquifer (Al–Katheeri, 2006).

Computer models of groundwater flow can be utilized to evaluate the feasibility of ASR prior to conducting costly field tests (Lowry and Anderson, 2006). The computer models can be used to simulate the hydraulic head build-up of the injected freshwater at a selected storage site through an injection well/wells, the contaminant transport of the water over time, and the efficiency of different recovery schemes (Khadri and Pande, 2016). The model which have been developed by Hutchinson (1998) aimed to simulate aquifer storage recovery of excess desalinated seawater in Al-Ain area, Abu Dhabi Emirate. Another ASR system pilot tests has been carried out in Sharjah Emirate at Nizwa area (Sharjah Electricity & Water Authority, 2009) and was proposed to achieve strategic storage and to meet the water demand.

2.2 Advantages of ASR

One of the advantages of implementing ASR systems is that subsurface storage can store a large volumes of water and it requires only a small footprint above ground, whereas the amount of water that can be stored at the surface depends on the capacity of the surface storage reservoirs (Maliva et al., 2007; Rambags et al., 2013). Therefore, aquifer storage and recovery is considered cost-effective technique as compared to above ground alternatives that require the construction of water treatment plants and surface reservoirs as well as huge land requirements. In addition, there may be insufficient space for above groundwater storage especially in urbanized areas (Maliva et al., 2009b; Dawoud, 2014).

The ASR has proven performance in many countries such as United States, Netherlands, England, Belgium and Australia (Wright, 2004; Castro, 2011; Rambags et al., 2013). Other advantages and purposes of the ASR system to the Eastern District of Abu Dhabi Emirate are as follows:

- Replenishment of depleted aquifer systems (Dawoud, 2014) such as in Al-Khaznah - Remah areas and to meet the variation when the demand is high.
- Strategic reserves and a long-term storage system of drinking water in case of any emergency circumstances (Ali and Dawoud, 2007).
- Improving the native groundwater quality by recharging with high quality injected water (Brown et al., 2005; Rambags et al., 2013).
- ASR systems has a low vulnerability of contamination whether it is natural, accidental or intentional (Maliva and Missimer, 2008).
- The recovered water requires no treatment other than disinfection (Maliva et al., 2009b).

- Easy to operate if accurately designed (Al–Katheeri, 2006).
- It can minimize the seawater intrusion and avoid land subsidence (Dillon et al., 2006).

2.3 ASR Design and Operation

There are several factors that need to be taken into consideration when determining the feasibility and designing of an ASR system (Brown et al., 2005; Missimer and Maliva, 2010b; Rambags et al., 2013; Maliva et al., 2015). The factors need to be addressed to determine the chance for implementing an ASR project are listed below.

2.3.1 Determine the Recharge Objective

The main step in designing an ASR system is to determining the recharge objectives which can be strategic storage and security, improving the quality of the native groundwater or other objectives (Rambags et al., 2013). If there are multiple objectives, it is important to prioritize the objectives and distinct between the primary objective of the ASR system and the secondary objectives. The main recharge objective in this thesis is to provide an uninterrupted drinking water supply and provide a strategic reserve to be used during any emergency situation in Al-Ain region, Abu Dhabi, UAE.

2.3.2 Water Demand, Water Source and Storage Requirement

Water Demand: A successful ASR system should have a sufficient demand for the recovered water in the future (Maliva et al., 2007). Therefore, it is essential to evaluate the current and projected water demand during the first steps of an ASR feasibility study. According to Rambags et al. (2013) daily and monthly water demand data over a period of a decade or more should be evaluated. This data gives valuable information about the volume of water required for a recovery to meet system demands. According to statistics center of Abu Dhabi, Energy and Water Report (SCAD, 2016) the consumed desalinated water in Al-Ain region is 297 MCM in 2016 compared to 259 MCM in 2011 while the per capita average daily consumption is 1.1 cubic meter.

Water Source for Storage: For an ASR system to be feasible, it is essential to have surplus freshwater available for storage (Brown et al., 2005). Sources of water could be a storm water, reclaimed water, desalinated seawater, or groundwater from other aquifers can be used for storage. Daily water supply data over a period of a decade or more should be evaluated, including averages, monthly variability, observed trends and expectations.

Storage Requirement: The amount of the water can be estimated based on the variability of water demand, water supply and water quality (Maliva et al., 2009b; Missimer et al., 2012). In other words, the rate in which water must be injected and recovered during an operational cycle can be estimated.

2.3.3 Hydrogeology

Assessment of the hydrogeological conditions in the vicinity of the ASR project site is required because it is directly related to the recovery efficiency of the system (Maliva et al., 2009b) and will control the movement of the injected water within the aquifer storage zone (Brown et al., 2005). ASR system will have a low recovery efficiencies if local hydrological conditions are unfavorable as the injected water should not travel away from the recharge location. Therefore, it require a favorable site specific hydrogeological conditions for successful implementation of the ASR system.

Assessing the main aquifers characteristics such as, lithology and structural elements (fractures, bedding, and joints), aquifer dimensions and extent, confining layer dimensions and extent, geochemical composition or reactivity of the aquifer matrix, salinity and water quality of native groundwater, and region groundwater flow.

The main aim of the characterization and assessment of the hydrogeological conditions is to identify the positive characteristics of the subsurface, such as zones with high porosity and permeability that would be promising for water recharge, as well as the negative characteristics such as the occurrence of contaminations or low permeability layers.

The salinity of the native groundwater should be determined as it affects the recovery efficiency of the ASR system by mixing between the injected water and native saline groundwater forming a bubble (Lowry and Anderson, 2006) that drifts upward due to differences in density as presented in Figure 7. The formed bubble can be monitored with time if well designed surface geophysical program such as surface electrical resistivity and borehole electrical tomography are established in the site area (Maliva et al., 2009a, 2015).

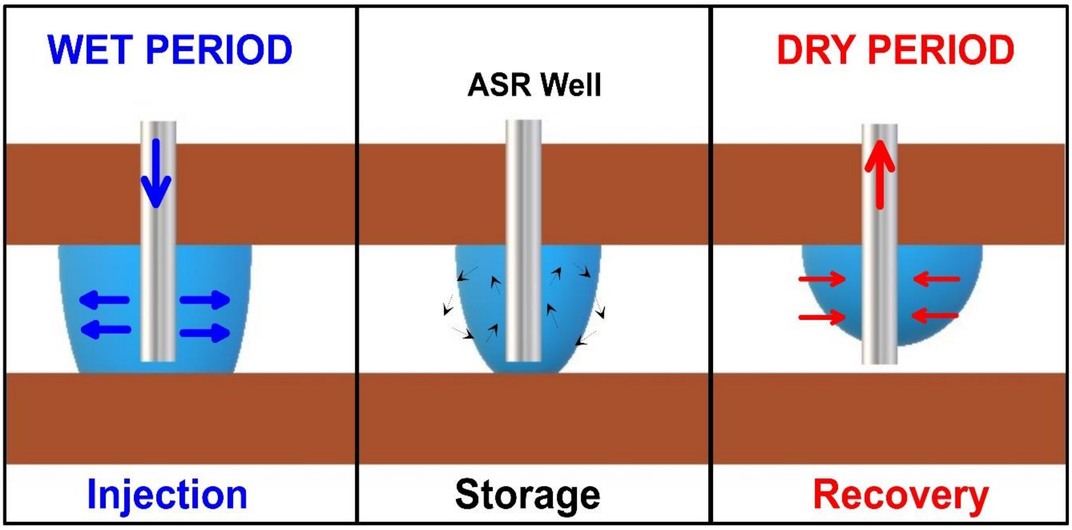


Figure 7: Loss of freshwater due to upward bubble drift in brackish aquifer

The regional groundwater flow should be taken into consideration (Vacher et al., 2006) to avoid the possibility of the injected water to move or loss during recovery as a result of lateral bubble drift (Zuurbier et al., 2013) as presented in Figure 8.

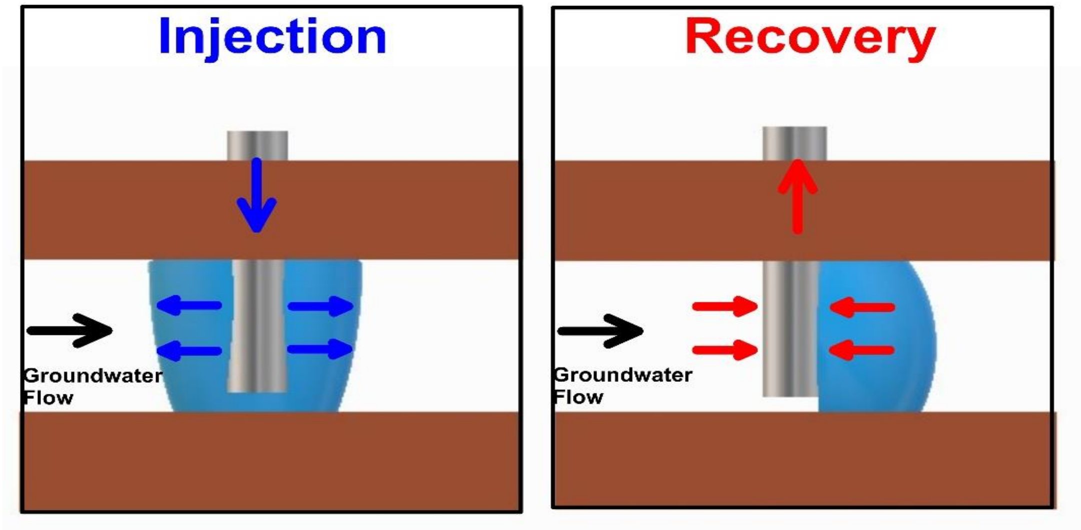


Figure 8: Drift of the injected water outside the ASR well zone

2.3.4 Financial Feasibility

The financial feasibility of the ASR system is dependent on the total costs. Therefore, to consider if the ASR system is an effective option (Maliva et al., 2015), it is important to know whether the ASR system will store water with lower costs than above ground storage option (Castro, 2011).

2.3.5 Environmental Feasibility

Adverse Environmental impacts such as contamination of the groundwater, changes in the groundwater level, or unwanted changes in the salt-freshwater interface could result from the construction of the ASR system (Missimer and Maliva, 2010b). Therefore, a full environmental impact assessment study should be conducted prior to the construction of any ASR system (Woody, 2008; Page et al., 2017).

Chapter 3 : Study Area

3.1 Al-Ain Region

The study area is Al-Ain region (Al-Ain Basin) which is located at the Eastern part of Abu Dhabi Emirate, UAE. Al-Ain region is near to the western border of Sultanate Oman and it is considered one of the largest oases of the Arabian Peninsula, due to its distinctive location which allow the city to receive a plentiful of surface and subsurface drainage from the Oman Mountains (Al-Hajar Mountains) to the East of the city (El-Ghawaby and El-Sayed, 1997) as presented in Figure 9**.**

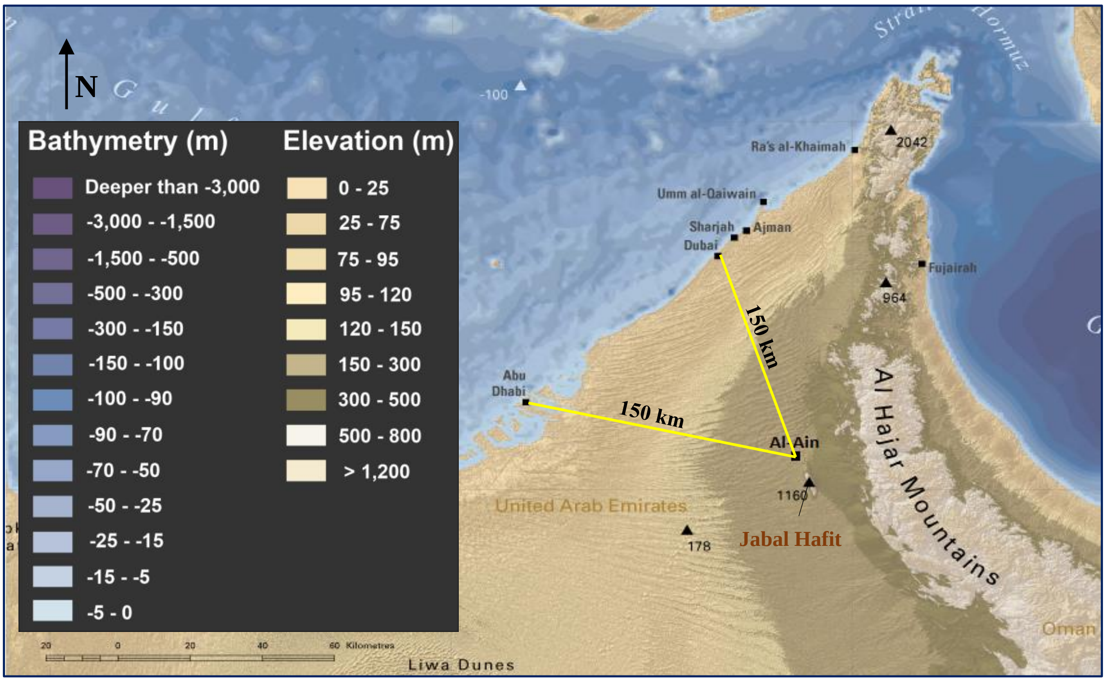


Figure 9: Al-Ain region location (adapted from EAD (2011b))

The freeways connecting Al-Ain region with Abu Dhabi and Dubai Emirates forms a geographic triangle with approximately 150 km distance from Al-Ain to Dubai and Abu Dhabi Emirate. Sultanate of Oman lies to the east, where Dubai, Sharjah, Ras

Al-khaimah and Fujairah lie to the north, Abu Dhabi to the west, and Saudi Arabia to the south.

The city is the fourth largest city in UAE and the second largest city in Abu Dhabi Emirate. It covers a total area around 15,100 km^2 with population of 0.76 million (26.4% of Abu Dhabi total population which is estimated to be inhabit 1.8 million) (SCAD, 2017).

Al-Ain region is famous with Jabal Hafit which has an elongated saddle-shaped mountain with an average of height 1110 m. Jabal Hafit northern parts lies with the UAE whereas most of the southern part is located within the Sultanate of Oman (El-Ghawaby and El-Sayed, 1997).

The study area is almost the entire Al-Ain region as presented in Figure 10 and the coordinates of the study area boundaries are listed in Table 1.

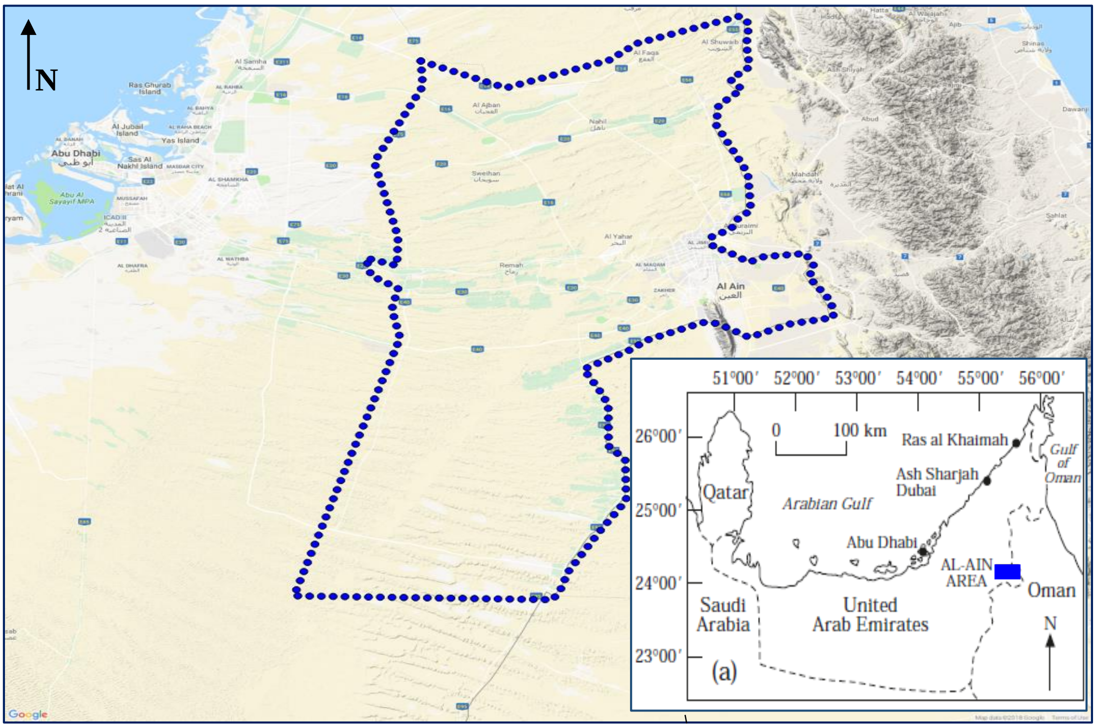


Figure 10: Satellite image of the study area boundaries

Table 1: Study area boundary coordinates

Boundary Points	Decimal, degree		UTM40	
	Easting	Northing	Easting	Northing
BP1	55.79300	24.79507	377994.443	2742795.871
BP2	55.81321	24.77500	380018.813	2740554.451
BP3	55.81661	24.67164	380263.290	2729105.614
BP4	55.77923	24.64290	376452.366	2725956.028
BP5	55.79727	24.61672	378253.417	2723040.732
BP6	55.75565	24.57374	373996.247	2718318.899
BP7	55.74724	24.53514	373105.713	2714051.933
BP8	55.81947	24.41825	380312.268	2701043.781
BP9	55.82491	24.32707	380778.889	2690942.304
BP10	55.79200	24.30243	377416.171	2688242.491
BP11	55.78555	24.28615	376745.821	2686445.358
BP12	55.74598	24.26549	372708.835	2684193.358
BP13	55.74408	24.23912	372489.434	2681274.536
BP14	55.82405	24.20542	380577.903	2677472.232
BP15	55.94322	24.22473	392697.089	2679513.842
BP16	55.96121	24.19447	394498.924	2676149.557
BP17	55.95484	24.16806	393830.533	2673229.950
BP18	55.99965	24.10558	398332.573	2666278.452
BP19	56.00881	24.07119	399237.213	2662463.610
BP20	55.82825	24.02502	380837.270	2657492.598
BP21	55.73076	24.05652	370953.235	2661067.273
BP22	55.47730	23.94433	345045.259	2648899.306
BP23	55.52925	23.85167	350226.660	2638581.563
BP24	55.52830	23.75637	350020.580	2628029.921
BP25	55.56619	23.72232	353843.651	2624220.173
BP26	55.56958	23.62910	354086.169	2613893.810
BP27	55.44658	23.45134	341324.061	2594340.440
BP28	55.41886	23.39019	338417.385	2587600.506
BP29	54.86763	23.38884	282068.047	2588175.644
BP30	55.07915	24.01220	304622.112	2656910.587
BP31	55.06482	24.07686	303262.606	2664092.065
BP32	55.07493	24.13173	304374.500	2670155.380
BP33	55.01703	24.15928	298532.154	2673288.119
BP34	55.00966	24.20173	297850.441	2678001.331
BP35	55.07173	24.19047	304138.643	2676665.334
BP36	55.01882	24.43698	299151.959	2704045.064
BP37	55.11979	24.62085	309667.945	2724268.000
BP38	55.11440	24.67753	309207.984	2730553.067
BP39	55.29723	24.61717	327628.694	2723625.861
BP40	55.52135	24.68578	350402.169	2730961.707
BP41	55.57849	24.72697	356231.194	2735461.788

3.2 Geomorphology and Geology of the Study Area

Geomorphologic features have a significant role in the movement of the surface and subsurface water (Rizk and Alsharhan, 2003). Therefore, Al-Ain region has better fresh groundwater underflow through the alluvial sediments in wadis drained from Oman Mountains (Al-Hajar Mountains) and periodic storm runoff from water concentrated in wadis as compared to the rest of the country (Murad et al., 2009).

There are many features present in Al-Ain region shown in Figure 11 and can be divided into six (6) geomorphic units surrounding Al-Ain basin according to (El-Ghawaby and El-Sayed, 1997). These units are; (1) Mountains, (2) Gravel Plains, (3) Drainage basins, (4) Sand Dunes, (5) interdune areas and (6) inland sabkhas. The geomorphic units are described as follows.

3.2.1 Mountains

The main mountains in Al-Ain region are Jabal Hafit, Jabal Moundassah, Jabal Malaqet, Jabal Al-Oha and Jabal Huwayah as presented in Figure 11. Jabal Hafit is the most noticeable feature in Al-Ain region which is a tertiary asymmetrical anticlinal structure (elongated saddle-shaped) with an average of height 1,110 m above sea level and extending about 30 km and width of 4 km (El-Ghawaby and El-Sayed, 1997).

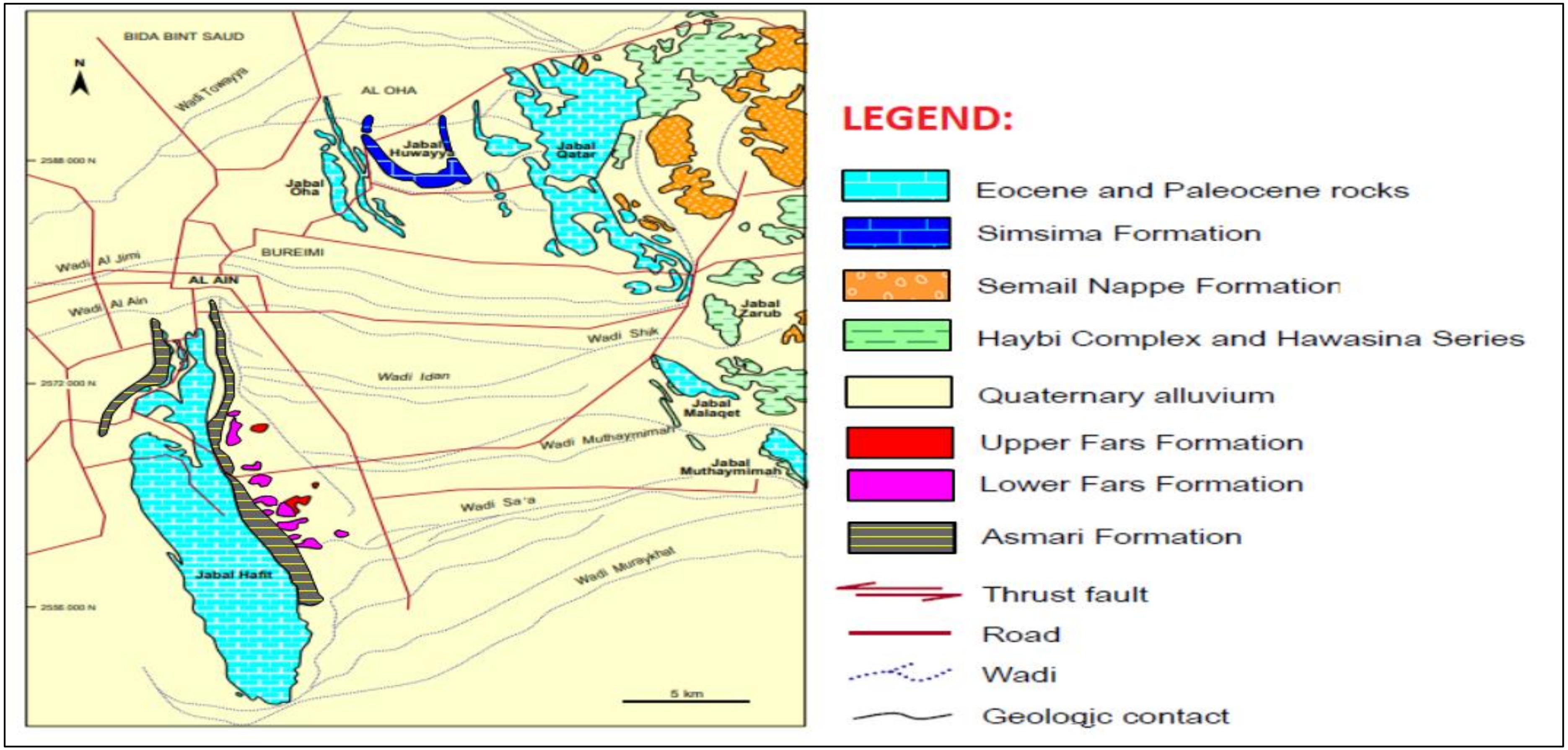


Figure 11: The hilly area where bedrocks outcrops to the southeast (Hunting Geology and Geophysics Ltd., 1979)

3.2.2 Gravel Plains

Two gravel plains exist in the eastern part of Al-Ain region, one of which fringes from Oman Mountains and reach its maximum development in Al-Jaww Plain that lie between Jabal Hafit and Oman Mountains (Hunting Geology and Geophysics Ltd., 1979) as shown in Figure 12. Al-Jaww Plain is mostly covered by quaternary deposits and consists of gently inclined gravels and sand plains formed and built-up by the alluvial fans deposited by streams and wadis dissecting the Oman Mountains (El-Ghawaby and El-Sayed, 1997). Three alluvial fans within the plain has been identified (Al-Shamsei, 1993) namely; Zarub fan in the north, Mundassah fan in the middle and Arjan fan in the south.

The unique location of Al-Jaww plain allows it to receive a plentiful recharge of the Quaternary aquifer from the rainfall on Oman Mountains which is considered as the main source of recharging the Quaternary aquifer. The Quaternary aquifer is also recharged by percolation of the rainfall in the permeable limestone rocks of Jabal Hafit and infiltration the interdune areas and gravels plains of Jabal Hafit. It also have considerable share of Abu Dhabi's freshwater resources (Murad et al., 2009).

The second plain exists around Jabal Hafit, which is formed as a result of weathering and erosion of the rocks (carbonates) from Jabal Hafit (Al-Shamsei, 1993). Therefore, it appears light in color on satellite image as presented in Figure 12.

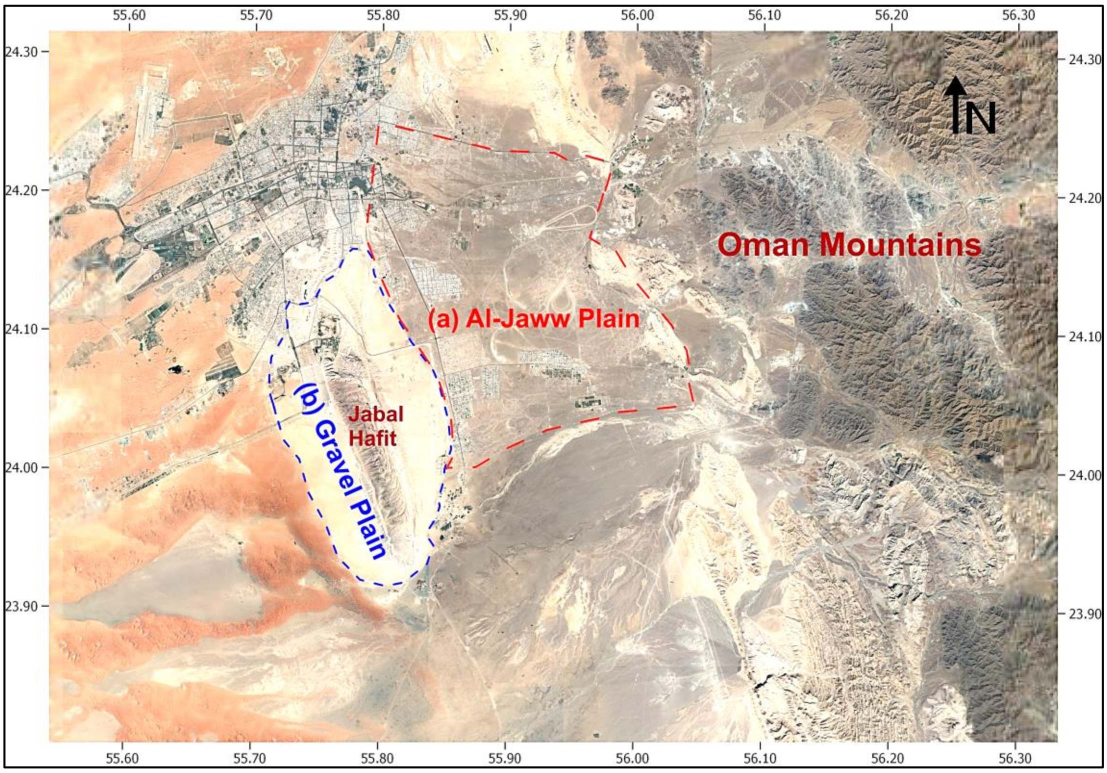


Figure 12: Satellite image showing (a) Al-Jaww Plain which lies between Jabal Hafit and Oman Mountains (b) Gravel Plain around Jabal Hafit

3.2.3 Sand Dunes

Sand dunes represents the Aeolian system which is one of the three main landforms system. This system covers about 90% of the total area of UAE (Al-Shamsei, 1993) and they dominate mainly the northern, western and southern parts of Al-Ain region (El Mahmoudi, 2003). However, the rapid developments and urbanization in Al-Ain region is growing continuously which reduce the presence of the sand dunes in the western part as presented in Figure 13.

All types of sand dunes and patterns are represented in the UAE which are shaped by variations in wind regime, sand supply, and local relief (El Mahmoudi, 2003). According to Abu-Zeid et al. (2001) and El Mahmoudi (2003), Barchan-linear dunes occupy the northern and western parts of Al-Ain area while the star dunes occupy the southeastern part near Al-Wagan Area (Abu-Zeid et al., 2001; El Mahmoudi, 2003).

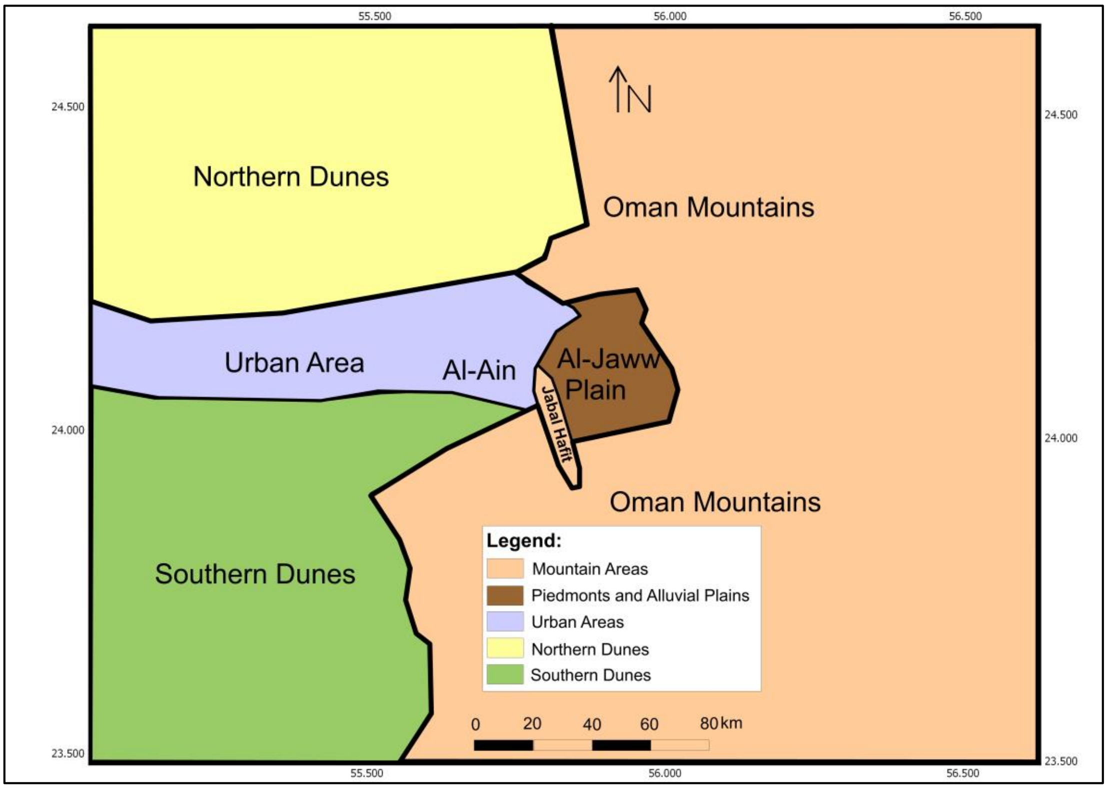


Figure 13: Geomorphological provinces surrounding Al-Ain region (adapted from Al-Nuaimi (2003))

3.2.4 Drainage Basins

There are two systems of drainage in Al-Ain region, namely Oman Mountains drainage system and Jabal Hafit drainage system (Al-Shamsei, 1993).

The drainage pattern is generally dendritic within the Oman Mountains due to the massive igneous rocks. However, in some areas controlled by faults, the pattern is rectangular and in areas of gentle slopes as in Al-Jaww Plain, the patterns change to braided. The drainage pattern of Jabal Hafit is generally radial, but on a basin scale, it ranges between braided to dendritic (Al-Shamsei, 1993). Drainage basins in Al-Ain region are presented in Figure 14.

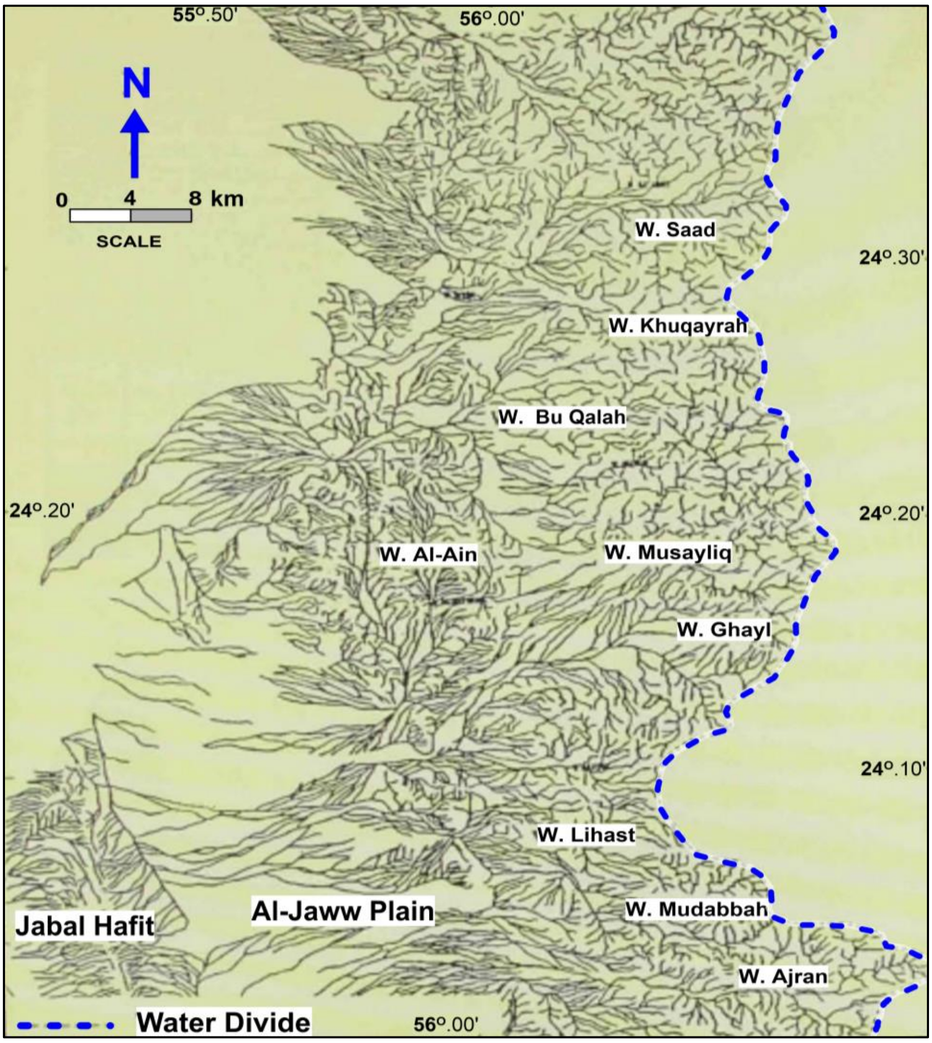


Figure 14: Drainage basins in Al-Ain region; basins of northern Oman Mountains and basins of Jabal Hafit (adapted from Al-Shamsei (1993))

3.2.5 Inter-dune Areas

Areas occupied by ablation hollows and Aeolian sands are called inter-dune areas. They are described by Hunting Geology and Geophysics Ltd. (1979), as ablation hollows and flats.

3.2.6 Inland Sabkhas

Low lands occupied by evaporitic sediments and are sites of groundwater discharge are called Inland Sabkhas it occurs where the water table lies very shallow to the surface and it is considered as a good indicator of periods with higher water tables. Examples of inland Sabkhas are Sabkhat Al-Thwaymah along Al-Ain-Al Wagan road and Sabkhat Al-Khatam along Al-Ain- Abu Dhabi road (Mahgoub, 2008).

3.3 Hydrogeological Settings of the Study Area

Four main aquifers exists in the UAE according to Rizk and Alsharhan (2003). The four aquifers (Rizk and Alsharhan, 2003; Brook and Dawoud, 2005) include the Limestone aquifers, Ophiolite aquifer and the two Quaternary aquifers which are considered the most important aquifers in the UAE namely, Gravel aquifers and the Sand Dune aquifers (Alsharhan et al., 2001) as presented in Figure 15.

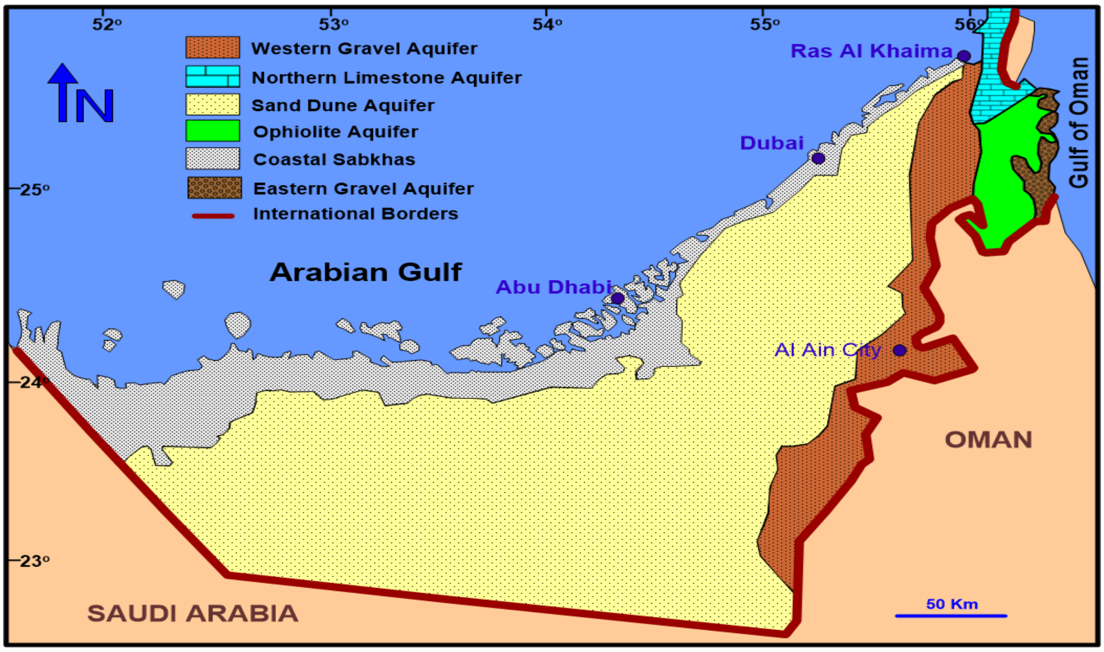


Figure 15: Main aquifers in UAE (adapted from Rizk and Alsharhan (2003))

3.3.1 Classification of Aquifers

Each aquifer in the UAE has its own characteristics and water potentiality. The main aquifers exist in UAE are described below according to Alsharhan et al. (2001) and (2003).

3.3.1.1 The Limestone Aquifers

The limestone aquifer includes two important aquifers in UAE; the Northern Limestone aquifer or Wadi Al Bih aquifer (not included in the study area) and the other aquifer is Jabal Hafit Limestone aquifer which exist south of Al-Ain region. The aquifer in Jabal Hafit area is Limestone of middle Eocene Dammam Formation and is characterized by extensive dolomitization as well as faults, voids, and heterogeneous secondary porosity and permeability (Brook and Dawoud, 2005).

3.3.1.2 The Ophiolite Aquifer

This aquifer is characterized by compact igneous and metamorphic rocks (Electrowatt, 1981; Rizk, 1998). The groundwater occur in fractures, joints and weathering of the Semail Ophiolite and the Hawasina beds of the Northern Oman Mountains and considered as a good aquifers (Rizk and Alsharhan, 2003).

3.3.1.3 Gravel Aquifers

The most important aquifer in the UAE as it is considered the largest quantity of fresh groundwater (Alsharhan et al., 2001). The gravel aquifers occur in the alluvial deposits of the piedmont plains surrounding Oman Mountains from the west and east. Gravel aquifer is divided into the eastern gravel aquifer and western gravel aquifer as presented in Figure 16. The eastern gravel aquifer is away from the study area (Al-Ain region), it is composed of a series of alluvial flats.

In the study area, the Quaternary alluvium of the western gravel aquifer is composed of an approximately 60 m sequence of sand and gravel with thin layers of silt and clay (Alsharhan et al., 2001; Rizk and Alsharhan, 2003; Brook and Dawoud, 2005).

Three main Quaternary western gravel aquifers occurs within the study area according to (EAD) Environment Agency - Abu Dhabi (2011b), as presented in Figure 16; (1) Quaternary Sand and Gravel aquifer underlain by the upper Fars Formation (sandstone, siltstone, mudstone, and marl) as basal unit (Khalifa, 2004) located to the west of Al-Ain region, (2) Quaternary sand and gravel aquifers east of Jebel Hafit (Al-Jaww Plan) which is underlined by the upper Fars Formation and lower Fars Formation (evaporite beds of anhydrite, gypsum, halite, and celestite with claystone, mudstone, and few limestone/dolomite) as a basal Unit, and (3) Quaternary Sand and Gravel Aquifer underlain by tectonically emplaced marlstones and shales as main basal unit with occasional limestone layers (EAD, 2011c).

The thickness of Quaternary gravel aquifer to the west of Jabal Hafit varies from few meters to more than 100 m (El Mahmoudi, 2004) and it is largely unconsolidated to slightly consolidated (Jorgensen and Petricola, 1994). The thickness of permeable layers in Al-Jaww Plain ranges from approximately 45 m close the northeastern of Al-Jaww Plain to around 100 m in the southeast of Jabal Hafit and around 130 m near the western flank. Along Oman Mountains in the northern dune area, the thickness of the aquifer is estimated more than 75 m while the thickness of the permeable layers decreases to less than 50 m at about 20 km west of the mountain. In the north central part of Eastern District, the aquifer thickness ranges from 30 and 50 m and towards the extreme northwestern corner the thickness is slightly increases to more than 50 m towards the northwestern area of the Eastern District (Al Shahi, 2002).

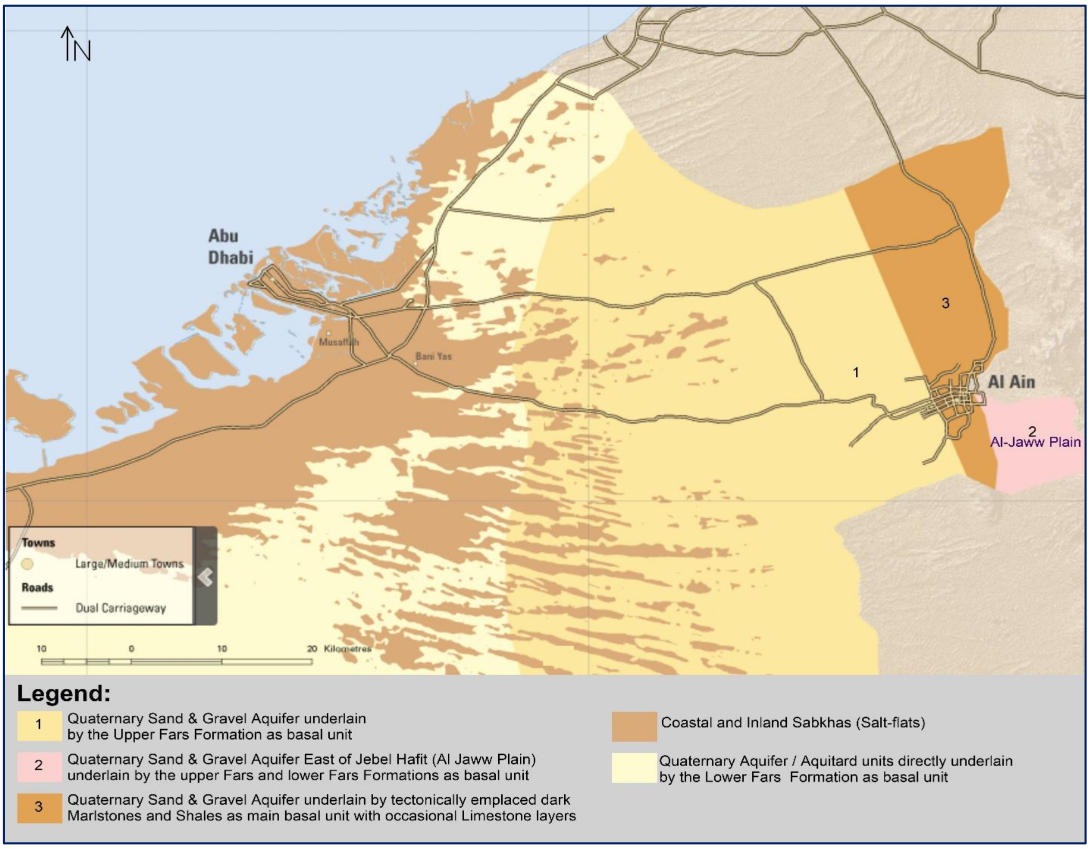


Figure 16: Three main Quaternary aquifers in the study area (adapted after EAD (2011c))

3.3.1.4 Sand Dune Aquifer

Sand dunes cover about seventy four percent (74%) of the total area of the UAE. The elevations of the sand dunes varies from sea level at the western coast to around 250 m above ground level in the Liwa - Al-Batin basin, south central part of UAE (Rizk and Alsharhan, 2003).

3.3.2 Groundwater Flow Systems

Groundwater flow systems are classified according to the residence time into local, intermediate, and regional flow systems (Alsharhan et al., 2001). The three types of groundwater flow systems exist in UAE as presented in Figures 17 and 18.

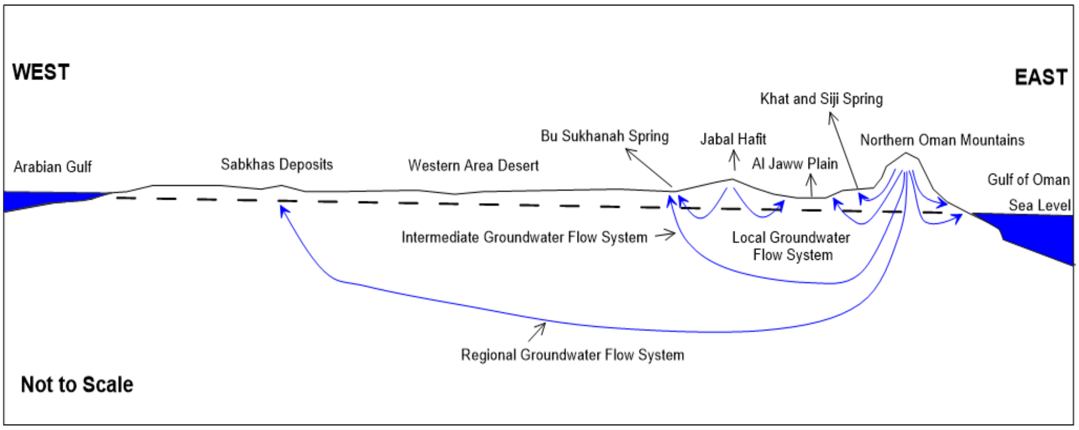


Figure 17: Groundwater flow systems in UAE (adapted from Alsharhan et al. (2001))

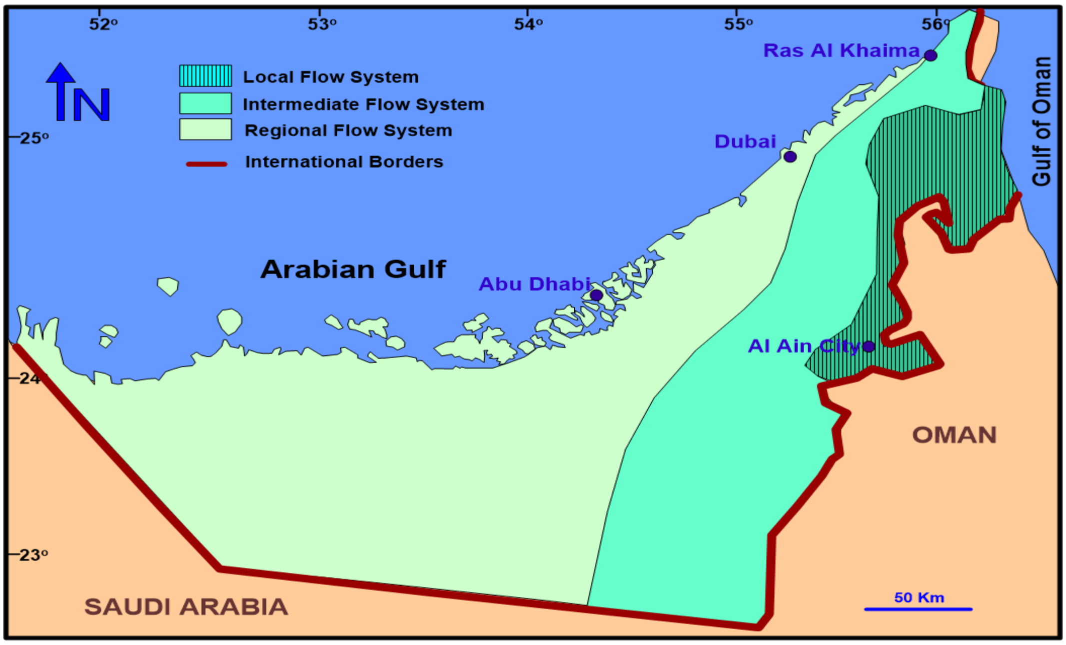


Figure 18: Approximate distribution of groundwater flow systems in the UAE (adapted from Rizk and Alsharhan (2003))

The local groundwater flow system has short residence time and occurs only in the eastern mountains (Jabal Hafit and Oman Mountains) where the hydrologic cycle is fast. The quality of the water in this system is considered good and it belongs to HCO_3^- water type and contains Mg^{+2} ions (Alsharhan et al., 2001) such as those exist in Al-Jaww Plain and Khatt (Ras Al Khaimah) springs (Al Shahi, 2002).

The intermediate groundwater flow occur Al-Ain Al Fayda area. This system has a moderate residence time and the quality of this water is mainly brackish and it belongs to SO_4^{-2} water type and contains Ca^{+2} ions.

The regional groundwater flow system discharge into the coastal areas (towards the Arabian Gulf). This system has a long residence time and the quality of this water is highly saline the water in this system belongs to Cl^{-1} water type.

3.3.3 Groundwater Recharge and Discharge

Precipitation in the UAE depends mainly on the geographic location, climatic conditions, and local topography (Al Shahi, 2002). According to National Center of Meteorology (2018), most of precipitation encountered during winter months (December to March). Furthermore, March has the highest record of precipitation according to several stations in Al-Ain region (NCM, 2018). Figure 19 present an example of one of the stations in Al-Ain region obtained from Al-Ain international Airport Station showing the mean of monthly total precipitation (mm) for the period from 1995 to 2017.

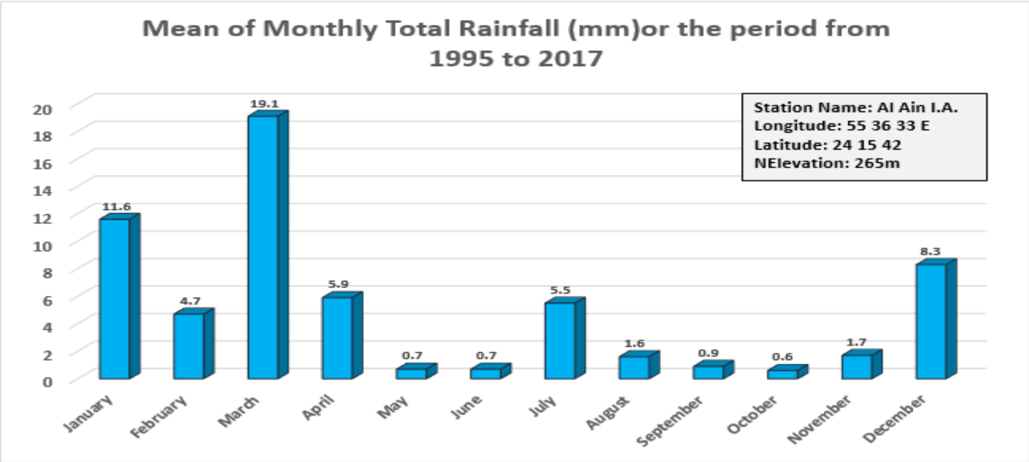


Figure 19: Mean of monthly total precipitation (mm) for the period from 1995 to 2017 (Al-Ain International Airport Station)

The precipitation increases in the north and east of the country while it decreases in the south and west (Al Shahi, 2002). Plentiful Recharge of the western gravel aquifer in Al-Ain region comes from rainfall on the western flank of Oman Mountains (Al-Hajar Mountains) and drains through wadis where it infiltrates and recharges the aquifer. The quaternary aquifer is also recharged by percolation of the rainfall in the permeable limestone rocks of Jabal Hafit and infiltration the inter-dune areas and gravels plains of Jabal Hafit (Murad et al., 2009). Therefore, the eastern mountains are the main recharge areas for groundwater in the UAE, where the Arabian Gulf is one of the main discharge areas along with Gulf of Oman as presented by the hydraulic head map for the sand and gravel aquifers (Alsharhan et al., 2001) in Figure 20.

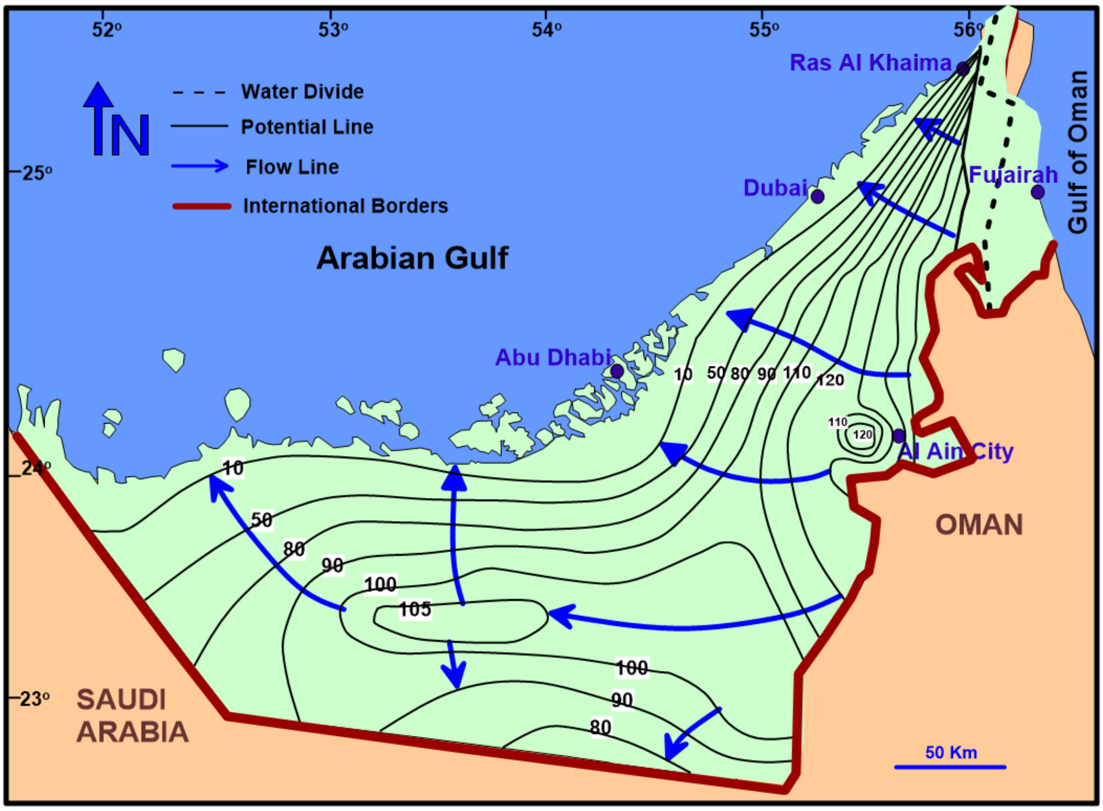


Figure 20: Hydraulic head map for the Sand and Gravel Aquifers (adapted from Alsharhan et al. (2001))

3.3.4 Groundwater Salinity

The salinity of the groundwater of the unconfined alluvial aquifer ranges from less than 1,000 ppm (Fresh) to more than 50,000 ppm (Saline) as shown in Figure 21. The salinity of the groundwater is increasing continuously in Al-Ain region due to the over-pumping practices which decline the groundwater level and quality (Dawoud and Sallam, 2012). The groundwater with low salinity (<1,000 ppm.) exists in Al-Jaww plain while the groundwater salinity of 1,000-7,000 ppm exists in northern and northwestern areas of Al-Ain region. Groundwater with total dissolved solids exceeding 10,000 ppm was found west and south of Al-Ain region.

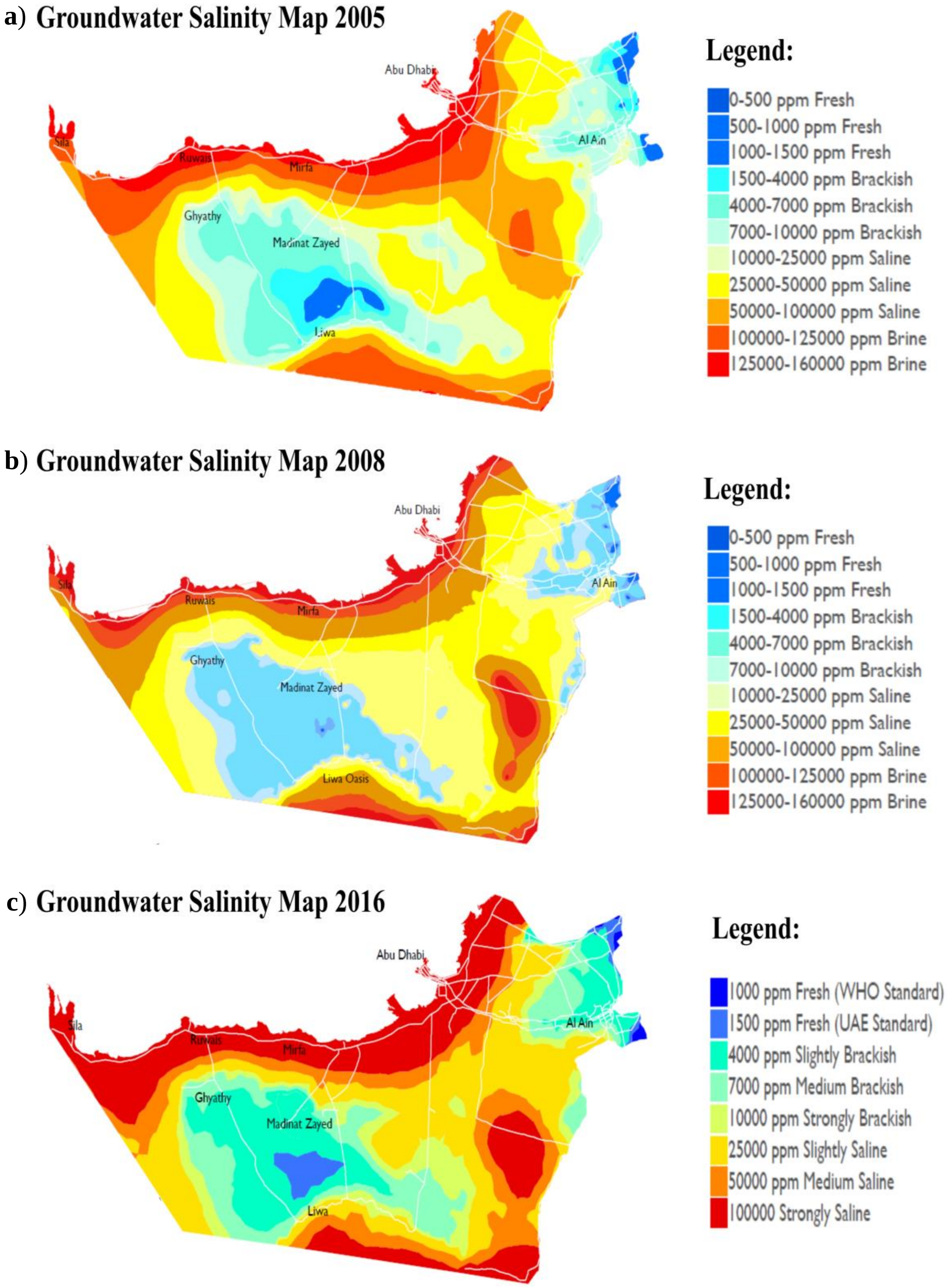


Figure 21**:** Groundwater salinity map a) 2005, b) 2008, and c) 2017 (EAD, 2016b)

Chapter 4 : ASR Sites Selection Criteria

Identification of specific sites for the proposed ASR System is very important in order to provide an accurate data input that will help in developing the numerical model (Brown et al., 2005; Woody, 2008). Multiple planning factors must be considered in the evaluation of the ASR site feasibility, some of these factors are source of recharge water, closeness to source, topography, permeability of near-surface materials, quality of water in the aquifer, quality of source water, and availability of the source water (Pettyjohn, 1985).

It is also important to study the ASR performance and operational parameters considering all the factors that can affect it (Lowry and Anderson, 2006; Zuurbier et al., 2013; Maliva et al., 2015; Rambags et al., 2013) before proceeding to the next step of large investments. The inadequate planning and improper ASR site characterization are the main causes of the ASR system failure (Missimer and Maliva, 2010b).

The ASR performance study need an extensive data and strong numerical models to reduce the uncertainties of the aquifer properties and to avoid the low recoverability of the injected water. A wide range of technologies are now available that ASR site selection stage to be studied and planned carefully in order to minimize the potential problems and maximize the performance (Maliva et al., 2015).

In addition to the hydrological characteristics related to ASR performance, other important ASR site selections factors (Brown et al., 2005; Woody, 2008) that should be taken into consideration are:

- Landuse (urban, suburban, wetlands, or landfill)
- Site accessibility (e.g. existing roads for access and construction)
- Protected wildlife habitats (endangered species)
- Existing groundwater users and impacts on their aquifers
- Availability of power and operational flexibility

Detailed study and knowledge of the hydrogeological characteristics and operational parameters are necessary for accurately selecting the best site for aquifer storage and recovery. To gain a hydrogeological understanding in the assessment level for the ASR system, Table 2 presents the hydrogeological and infrastructural criteria and its suitability assessment modified after Pyne (1995), Woody (2008), and Dillon and Jiménez (2008) that will help in defining the suitable sites for ASR system and disqualifying the sites that doesn't match the suitability assessment (Pyne, 1995; Woody, 2008; Dillon and Jiménez, 2008). A score of 1 is assigned for Poor/Not Suitable, 2 for Fair/Limited Suitability, 3 for Good/Suitable, and 4 for Excellent/Highly Suitable as presented in Figure 22.

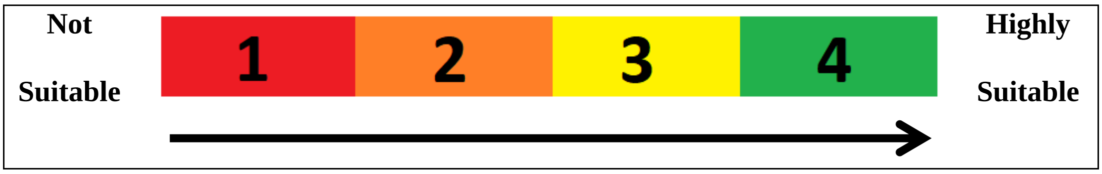


Figure 22: Suitability index

Table 2: Hydrogeological and infrastructural criteria and its suitability assessment modified after (Pyne, 1995; Woody, 2008; Dillon and Jiménez, 2008)

Characteristic	Criteria/Range	Suitability assessment	Status	Score
Thickness of the Aquifer (m)	<10	Thin layer, medium potential recovery rate	Fair	2
	10-50	Medium, high potential recovery rate	Good	3
	>50	Thick layer, low potential recovery rate	Poor	1
Permeability (m/s)	$<10^{-6}$	Very low, very limited suitability	Poor	1
	10^{-6}-10^{-5}	Low, limited suitability	Fair	2
	10^{-5}-10^{-4}	Medium, Suitable	Fair	2
	10^{-4}-10^{-3}	High, Suitable	Good	3
	$>10^{-3}$	Very high, suitable	Excellent	4
Aquifer confinement	Unconfined	Suitable	Good	3
	Confined	Highly suitable	Excellent	4
Uniformity of hydraulic properties	Homogeneous	Highly Suitable	Excellent	4
	Heterogeneous	Limited Suitability	Fair	2
Groundwater Salinity	Fresh (TDS <1,000 ppm)	Suitable for aquifer recharge	Excellent	4
	Brackish/Saline (TDS >1,000 ppm)	Brackish and saline groundwater may result in buoyancy effects	Fair	2

Table 2: Hydrogeological and infrastructural criteria and its suitability assessment modified after (Pyne, 1995; Woody, 2008; Dillon and Jiménez, 2008) (Continued)

Characteristic	Criteria/Range	Suitability assessment	Status	Score
Hydraulic gradient	Gentle Gradient (<0.1%)	Promote conservation of the injected water in the recharge zone	Excellent	3
	Moderate to Steep Gradient (>0.1%)	Possible flow of injected freshwater to from the recharge zone	Fair	2
Consolidation (Porous/Non-Fractured)	Consolidated	Highly Suitable	Excellent	4
	Unconsolidated	Suitable	Good	3
Aquifer Mineralogy	Unreactive	Highly Suitable	Excellent	4
	Reactive	Unsuitable	Poor	1
Redox state of native groundwater	Aerobic	Highly Suitable	Excellent	4
	Anaerobic	Unsuitable	Poor	1
Depth to Water Level (m)	<10	Limited Suitability	Fair	2
	10-30	Suitable	Good	3
	>30	Highly Suitable	Excellent	4
Well density	more than 5 wells within 1km radius	Limited Suitability	Fair	2
	1 to 5 wells within 1km radius	Suitable	Good	3
	No wells within 1km radius	Highly Suitable	Excellent	4

Table 2: Hydrogeological and infrastructural criteria and its suitability assessment modified after (Pyne, 1995; Woody, 2008; Dillon and Jiménez, 2008) (Continued)

Characteristic	Criteria/Range	Suitability assessment	Status	Score
Recharge Water Quality	Does not meet standards	Limited Suitability	Fair	2
	meet some standards	Suitable	Good	3
	meets all standards	Highly Suitable	Excellent	4
Distance to Source Water	Distance is 3 km	Limited Suitability	Fair	2
	1 km< distance to source< 3 km	Suitable	Good	3
	Distance to source less than 1 km	Highly Suitable	Excellent	4
Endangered species	High impact	Limited Suitability	Fair	2
	Somewhat impact	Suitable	Good	3
	No impact	Highly Suitable	Excellent	4
Predicted water supply exceeds demand	Demand exceeds predicted water supply	Not suitable	Poor	1
	Predicted supply exceeds demand	Highly Suitable	Excellent	4

4.1 Hydrogeological Characteristics

Hydrogeological characteristics were considered for the suitability assessment for ASR site, each has its own criteria/ranges and assumed score were assigned based on its suitability. The hydrogeological characteristics are described below.

4.1.1 Aquifer Confinement

Two types of aquifers can be present in the proposed site depending on the geological layers bounding it. First type is confined aquifer which is an aquifer covered with a top impermeable layer (e.g. Clay or Shale) and infiltration of water from ground surface does not reach the aquifer unless there is a seepage from the impermeable layer. Second type is called unconfined aquifer (phreatic or water table aquifer) where the top of the aquifer is overlaid by permeable and porous layer which can permit the water to infiltrate from ground surface and percolate to the water table.

The confined aquifer are not suitable for MAR techniques that rely on surface spreading methods (e.g. Infiltration Pond) since the layer overlaying the aquifer is impermeable. Both confined and un-confined aquifers can be suitable for ASR system (Dillon et al., 2006) but other hydrogeological criteria will help in the optimum ASR site selection (Stuyfzand et al., 2017).

4.1.2 Aquifer Permeability and Transmissivity

Suitable aquifer is a must in ASR system. A good hydraulic performance of the aquifer such as high infiltration rates and high storage capacity associated to the high permeability of the aquifer. For ASR sites, high permeability is recommended for an ASR site success while marginal low or very high permeability may perform well depend on the size of the ASR project (Woody, 2008). Permeability is proportional to the transmissivity and it is considered the most important factor to the success of an ASR system.

Transmissivity is the permeability of the aquifer times the aquifer's thickness and has a unit of ft^2/day or m^2/day. According to Brown et al. (2005), the ideal transmissivity which offers the best chance for an ASR success (Brown et al., 2005) ranges from 5,000 ft^2/day to 25,000 ft^2/day (465 m^2/day to 2,323 m^2/day) while according to Minsley et al. (2009), transmissivity of the aquifer is more favorable to be moderate (150-400 m^2/day) to allow the injected water to move easily and rapidly rather than high transmissivity which may result in very low recovery or loss of the injected water (Minsley et al., 2009).

4.1.3 Aquifer Thickness

Aquifer thickness is specifically defined as the aquifer saturated thickness. The potential recovery is strongly dependent on the aquifer saturated thickness. According to Woody (2008), aquifer thickness of an ASR system is considered ideal if it is more than 7.6 m (25 ft.). This is because a thin aquifer with high value of transmissivity could result in forcing the injected water to spread out horizontally forming an injection bubble (Vacher et al., 2006; Ward et al., 2007). Thus increasing the possibility that the stored water will migrate (Woody, 2008). However, it is still possible to inject water into thinner aquifers, but it would need careful study of the aquifer characteristics to insure that the stored water is recoverable.

Injecting water into a thinner aquifer with brackish native groundwater, will result in a buffer/transition zone between the injected water and the native groundwater further away from the ASR well as presented in Figure 23.

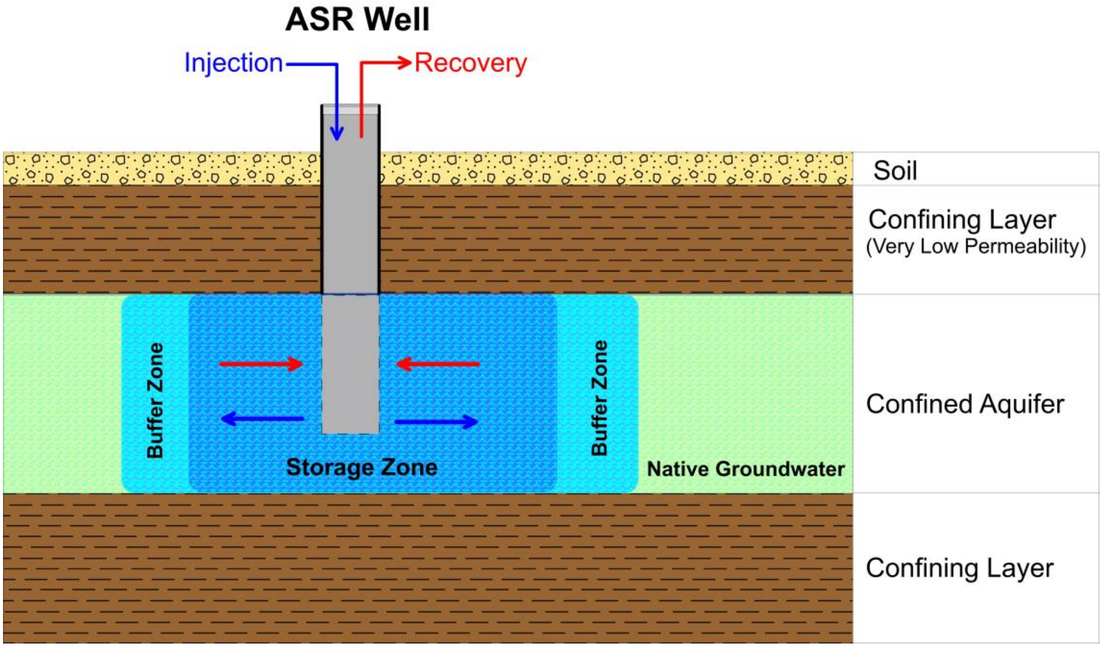


Figure 23: Schematic illustration of a buffer/transition zone between the injected water and the native groundwater in confined aquifer

Injected water into thinner aquifers are less subjected to lateral drift out of the well zone because the injected water (bubble) is wider unless the well density of the neighboring wells of the ASR system is high, which may result in losing the injected water to other wells (Woody, 2008). In addition, thinner aquifers are the less subjected to buoyancy effects which occur in the aquifers with total dissolved solids (TDS) exceeding 5,000 ppm of the groundwater (Pyne, 1995) and causes salinization at the bottom of the ASR well during recovery well.

4.1.4 Groundwater Depth

The groundwater depth is defined as the difference between the ground elevation and the water table elevation (water level) in the aquifer as presented in Figure 24.

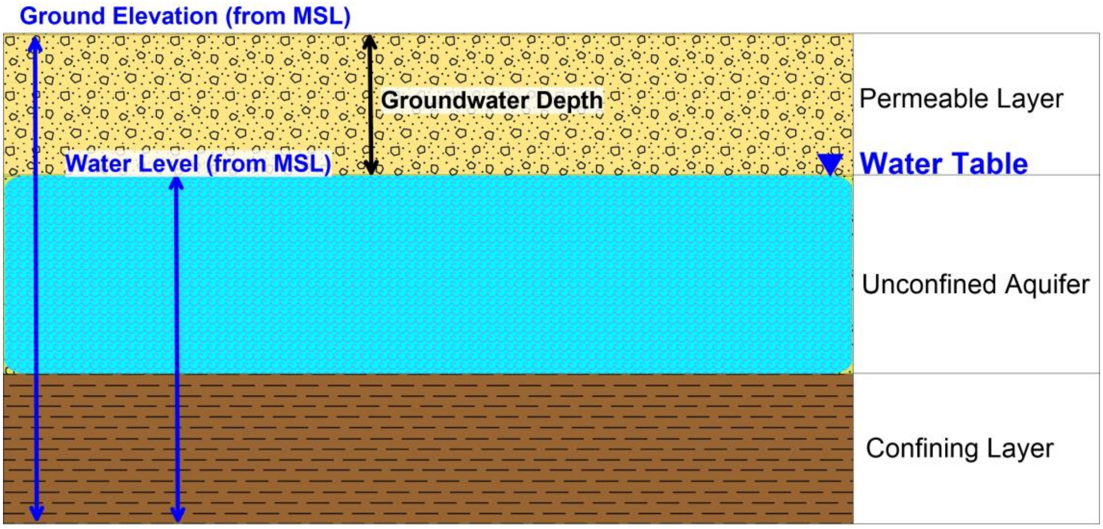


Figure 24**:** Schematic illustration of water level and water depth

The thickness of the unsaturated zone (yellow colored/permeable layer) should not be too high to minimize the energy costs during water recovery by the ASR well. In addition, surface material should be highly permeable to permit water to percolate and the unsaturated zone must exhibit high vertical permeability.

4.1.5 Aquifer Consolidation (Pore Type / Non-Fractured)

Most of the ASR wells are situated in porous and unconsolidated aquifers due to its advantage in natural purification capacities by fine grains or organic carbon in sediments (adsorption) compared to fractured or karstified aquifers. Therefore, porous and unconsolidated aquifers are more favorable for ASR system compared to fractured and karstified aquifers.

4.1.6 Uniformity of Hydraulic Properties and Topographic Slope

Heterogeneity in aquifer dimensions vertically and horizontally would result in ASR system failure if not studied in details to ensure the movement on the injected water (Missimer and Maliva, 2010b). Therefore, homogenous hydraulic properties were considered highly suitable in Table 2.

Topographic slope is not considered as a significant factor in implementing the ASR system, but it should be considered while implementing infiltration pond or other MAR technique.

4.1.7 Aquifer Salinity

The aquifers with saline or brackish water will have a buoyancy effect resulted from the different in densities between the injected water and the native groundwater (Brown et al., 2005; Lowry and Anderson, 2006; Vacher et al., 2006; Zuurbier et al., 2013). The freshwater will float upwards and denser water (brackish or saline) will be located in the lower parts of the recovery wells, which will reduce the recovery efficiency due to the decrease in the recoverable freshwater (Misut and Voss, 2007; Rambags et al., 2013). Figure 7 shows the ASR well phases (injection, storage, and recovery) and the buoyancy effect resulted from different qualities of injected water and the native groundwater (Pyne, 1995). For a successful ASR system, the quality of the native groundwater (salinity of groundwater) should not exceed 5,000 ppm (Minsley et al., 2009).

4.1.8 Regional Hydraulic Gradient

The regional hydraulic gradient should be limited and gentle to avoid drift of the injected water outside the ASR well zone (Figure 8), since this would result in low recovery efficiencies and loss during the recovery of the injected freshwater. In the study area, the average westward hydraulic gradient is 0.004 based on 100 meters of head change over a distance of 25 km (Hutchinson, 1998).

According to Brown et al. (2005), hydraulic gradient of less than 0.001 is considered ideal for an ASR system. This criteria has been studied and examined in an aquifer located in Washington, United States by a consulting company and found that >85% recovery efficiency was achieved with a hydraulic gradient of 0.0013 while zero recovery efficiency was found when the hydraulic gradient was 0.015 in a similar situation (Brown et al., 2005).

4.1.9 Redox State of Native Groundwater

Natural systems are considered as a good removal of pathogens and nitrogen which are considered the most common water quality issues (Dillon et al., 2006). Dillon and Jiménez (2008), suggested that specifically in aerobic aquifers, pathogen viruses, protozoa, and bacteria of wastewater origin could be inactivated if the residence time is sufficient. Therefore, aerobic aquifer is more suitable for ASR system.

4.1.10 Aquifer Mineralogy

Mineral dissolution and precipitation may occur as a result of the chemical disequilibrium between the injected freshwater and the native groundwater in the aquifer which can result in unwanted deterioration of the recovered water quality (Woody, 2008). Geochemical models can be used to predict the fluid-rock interactions if data are available on chemistry of water and aquifer mineralogy (Maliva et al., 2007).

4.2 Infrastructural Characteristics

Infrastructural characteristics were considered for the suitability assessment for ASR site. The Infrastructural characteristics are described below.

4.2.1 Distance to Source Water

As the distance to source water decrease, the installation of ASR system is considered least expensive (Woody, 2008). According to Minsley et al. (2009), the ASR project should be near to the source of water need to be injected (Minsley et al., 2009) while according to Brown et al. (2005), an ASR project is most feasible when the distance between injection wells to the source water is less than 4.8 km (Brown et al., 2005). In Al-Ain Region, water production plants are not available but water is supplied through pipelines to the existing pumping stations located in Al-Ain region via three sources, namely, from Shuweihat/Umm Al Nar desalination plant, Taweelah desalination plant, or Fujairah desalination plant or combination of the three according to TRANSCO (2013). The supply zones in eastern region of Abu Dhabi Emirate are presented in Figure 25.

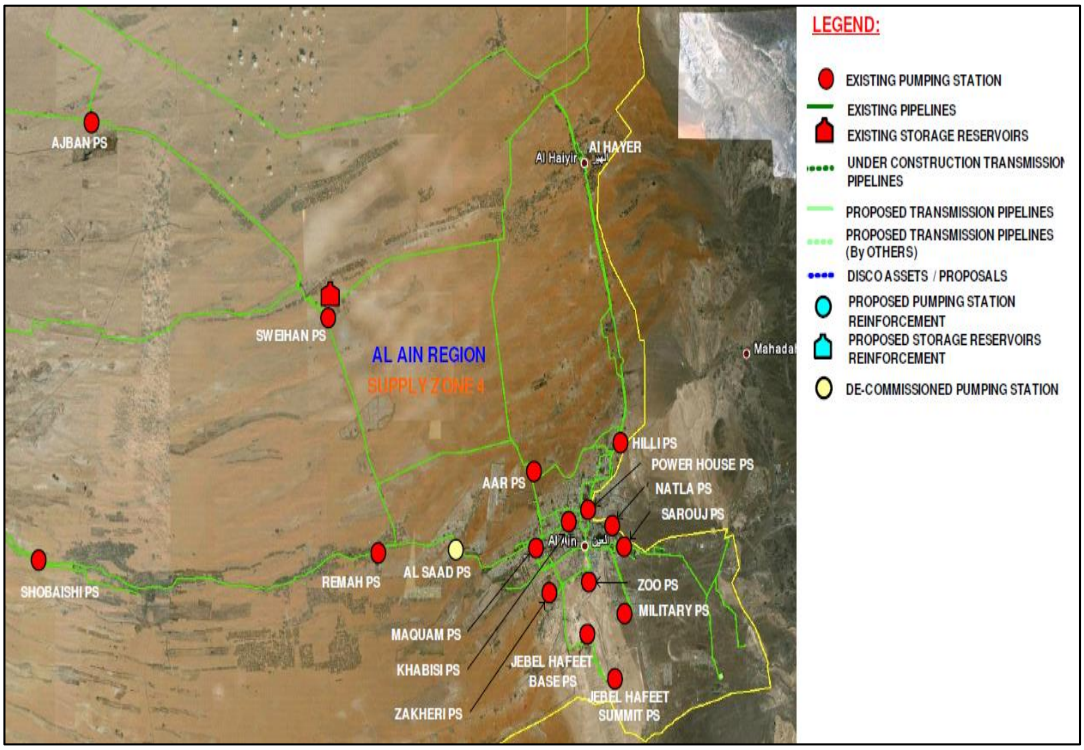


Figure 25: Eastern region of Abu Dhabi Emirate supply zones
(TRANSCO, 2013)

4.2.2 Well Density

Well density criterion is an indication of the probability that an ASR project might affect the nearby users wells' by declining or increasing the water levels while recovery or injection of the water (Woody, 2008).

4.2.3 Ecological Suitability

This criterion is mainly focused on the likelihood than an ASR project might adversely impact the protected species or habitat (Brown et al., 2005). The protected species and habitat exists within the study area according to EAD (2017), are Wadis in open terrain and Drainage channels (Flood plains, Jabal Hafit region), Mountain slopes, Screes and associated wadis, Sand Sheets and Dunes with Tree Cover, and Alluvial or Inter-dunal Plains (south of Al-Ain between Abu Dhabi/Oman borders) which are listed as a critical habitat (Table 5). Wadis in open terrain and drainage channels is found around Jabal Hafit (not including Jabal Hafit) and characterized by temporary water flow, seasonal ponds, and small number of permanent ponds (EAD, 2017b).

Table 3: Critical habitat and its location in Al-Ain region (EAD, 2017b)

Habitat	Location
Wadis in open terrain and drainage channels	Around Jabal Hafit (not including Jabal Hafit) and characterized by temporary water flow, seasonal ponds, and small number of permanent ponds.
Sand Sheets and Dunes with Tree Cover	Confined to the east of the Emirate, particularly around Al -Ain, but extending westwards to within 50 km of Abu Dhabi Island.
Alluvial or Inter-dunal Plains	South of Al-Ain between Abu Dhabi/Oman borders
Mountain slopes, screes and associated wadis	Confined to Jebel Hafit and adjacent Foothills

4.3 Scoring and Site Selection

Based in the available data collected from various literatures, field investigations, ACES (Arab Center for Engineering Studies), and EAD (Environment Agency – Abu Dhabi). A score was assigned to each criteria according to their suitability and importance. Total of 21 sites were evaluated in terms of hydrogeological and infrastructural characteristics previously explained in Table 4. The 21 sites in the study area are listed in Table 6.

Table 4: The evaluated 21 sites in the study area

S. No.	Site	S. No.	Site	S. No.	Site
1	Um El-Zumol	8	Nahel	15	Abu Karrayah
2	Al-Dhahir	9	Alajban	16	Al-Araad
3	Al-Khrair	10	Sweihan	17	Wagan
4	Ayn Al-Fayda	11	Remah	18	Al-Quaa
5	Bin Asmad	12	Al-Khaznah	19	Abu Huraibah
6	Al-Hayer	13	Al-Saad	20	Al-Bateen
7	Al-Shuwaib	14	Sayh Al-Hamah	21	Al-Shuaibah

A weighting factor was assigned to each hydrogeological and infrastructural characteristic based on its importance in the ASR selection and its effect on the efficiency of the ASR system based on previous investigations and cases of an implemented ASR system. The weighting factor values range from 1 to 4 based on its significance where 1 is the lowest significance while 4 is the highest significance. The weighting factor index is presented in Figure 26.

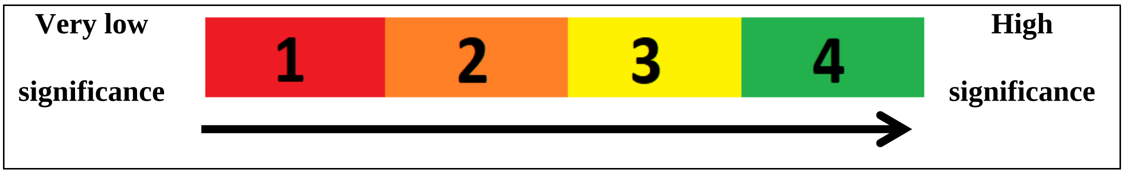


Figure 26: Weighting factor index

The weighting factor is then multiplied by the suitability score assigned for each criteria at each site separately to get the total score then the total score from the 15 criteria's is calculated to give the overall score of the site.

The highest weighting factor (4: High Significance) was given to thickness of the aquifer (m), permeability (m/sec), and groundwater salinity due to their Significance impact on the ASR system. Moderate weighting factor (3: Medium Significance) was given to aquifer confinement, uniformity of hydraulic properties, hydraulic gradient, depth to water level (m), predicted water supply exceeds demand and distance to source water. Low weighting factor (2: Low Significance) was given to consolidation of the aquifer, well density in the vicinity of the ASR project, recharge water quality, and endangered species while the very low weighting factor (1: Very Low Significance) is given to aquifer mineralogy and redox state of native groundwater. The score sheets for the 21 sites are given in Tables 5-11.

Table 5: Um El-Zumol, Al-Dhahir, Abu Huraibah score sheet

Site		Um El-Zumol		Al-Dhahir		Abu Huraibah	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	2	8
Permeability (m/sec)	4	4	16	4	16	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	4	16	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	3	6	3	6
Aquifer Mineralogy	1	4	4	4	4	1	1
Redox state of native groundwater	1	4	4	4	4	1	1
Depth to Water Level (m)	3	3	9	4	12	2	6
Well density	2	2	4	2	4	3	6
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	3	9	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		48	123	50	132	39	106

Table 6: Al-Shuaibah, Bin Asmad, and Al-Hayer score sheet

Site		Al-Shuaibah		Bin Asmad		Al-Hayer	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	2	8	3	12	1	4
Permeability (m/sec)	4	2	8	2	8	4	16
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	3	6	3	6
Aquifer Mineralogy	1	1	1	1	1	4	4
Redox state of native groundwater	1	3	3	3	3	2	2
Depth to Water Level (m)	3	2	6	3	9	3	9
Well density	2	3	6	3	6	2	4
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	3	9	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		41	106	42	111	43	111

Table 7: Nahel, Alajban, and Sweihan score sheet

Site		Nahel		Alajban		Sweihan	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	1	4	2	8
Permeability (m/sec)	4	3	12	3	12	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	4	8	4	8
Aquifer Mineralogy	1	1	1	4	4	1	1
Redox state of native groundwater	1	2	2	2	2	2	2
Depth to Water Level (m)	3	3	9	4	12	3	9
Well density	2	2	4	3	6	3	6
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	3	9	3	9	4	12
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		41	112	45	114	43	115

Table 8: Abu Karrayah, Al-Araad, and Al Wagan score sheet

Site		Abu Karrayah		Al-Araad		Wagan	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	1	4	3	12	3	12
Permeability (m/sec)	4	4	16	3	12	2	8
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	4	8	3	6
Aquifer Mineralogy	1	4	4	4	4	4	4
Redox state of native groundwater	1	3	3	2	2	2	2
Depth to Water Level (m)	3	4	12	2	6	2	6
Well density	2	2	4	2	4	3	6
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	3	9	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		46	117	44	114	43	110

Table 9: Ayn Al-Fayda, Al-Bateen, and Al-Shuwaib score sheet

Site		**Ayn Al-Fayda**		**Al-Bateen**		**Al-Shuwaib**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Permeability (m/sec)	4	3	12	4	16	4	16
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	4	12	2	6
Groundwater Salinity	4	2	8	2	8	4	16
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	3	6	4	8
Aquifer Mineralogy	1	1	1	4	4	4	4
Redox state of native groundwater	1	4	4	2	2	3	3
Depth to Water Level (m)	3	2	6	3	9	3	9
Well density	2	4	8	3	6	3	6
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	3	9	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		44	115	48	127	50	132

Table 10: Al-Khaznah, Al-Saad, and Al-Quaa score sheet

Site		**Al-Khaznah**		**Al-Saad**		**Al-Quaa**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Permeability (m/sec)	4	3	12	2	8	4	16
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	4	12
Groundwater Salinity	4	2	8	2	8	1	4
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	4	8	3	6
Aquifer Mineralogy	1	1	1	1	1	4	4
Redox state of native groundwater	1	2	2	2	2	2	2
Depth to Water Level (m)	3	3	9	3	9	3	9
Well density	2	3	6	2	4	2	4
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	4	12	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		43	117	38	110	46	121

Table 11: Sayh Al-Hamah, Al-Khrair, and Remah score sheet

Site		**Sayh Al-Hamah**		**Al-Khrair**		**Remah**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Permeability (m/sec)	4	3	12	4	16	2	8
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	4	12	2	6
Groundwater Salinity	4	2	8	4	16	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	3	6	3	6
Aquifer Mineralogy	1	4	4	4	4	1	1
Redox state of native groundwater	1	3	3	4	4	2	2
Depth to Water Level (m)	3	2	6	4	12	4	12
Well density	2	3	6	4	8	3	6
Recharge Water Quality	2	4	8	4	8	4	8
Distance to Source Water	3	4	12	3	9	3	9
Endangered species	2	4	8	4	8	4	8
Predicted water supply exceeds demand	3	4	12	4	12	4	12
TOTAL SCORE		46	118	54	142	42	113

After applying the score procedure on the 21 available sites, the overall all score out of 160 (maximum possible score) will indicate the best location for potential ASR system. The overall scores for the evaluated sites are listed in Table 12 and presented in Figure 27.

Table 12: Overall scores for the evaluated sites

S. No.	Site	Overall score	S. No.	Site	Overall score	S. No.	Site	Overall score
1	Al-Khrair	142	8	Al-Khaznah	117	15	Nahel	112
2	Al-Dhahir	132	9	Abu Karrayah	117	16	Bin Asmad	111
3	Al-Shuwaib	132	10	Ayn Al-Fayda	115	17	Al-Hayer	111
4	Al-Bateen	127	11	Sweihan	115	18	Al-Saad	110
5	Um El-Zumol	123	12	Alajban	114	19	Wagan	110
6	Al-Quaa	121	13	Al-Araad	114	20	Abu Huraibah	106
7	Sayh Al-Hamah	118	14	Remah	113	21	Al-Shuaibah	106

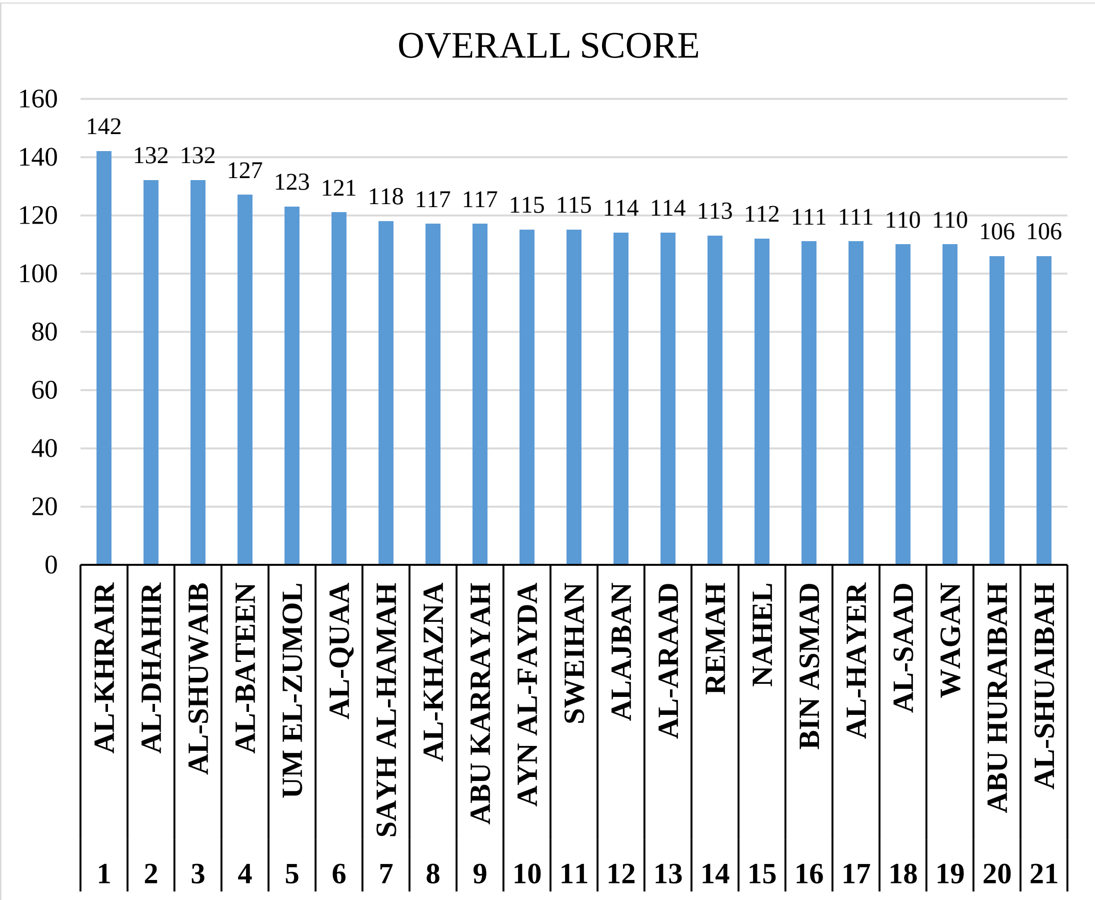


Figure 27: Overall scores for the evaluated sites

As shown in Figure 27, the overall score at the 21 sites are shown in blue bar. The highest score is Al-Khrair site followed by Al-Dhahir /Al-Shuwaib and Al-Bateen sites, respectively.

The same site selection procedure is repeated for the 21 sites based on the most important 7 hydrogeological criteria's to re-evaluate the possibility of finding another location for ASR system. The new score sheets for the 21 sites are given in Tables 13-19.

Table 13: Um El-Zumol, Al- Dhahir, and Abu Huraibah score sheet (Reduced)

Site		**Um El-Zumol**		**Al-Dhahir**		**Abu Huraibah**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	2	8
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	4	16	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	3	6	3	6
Depth to Water Level (m)	3	3	9	4	12	2	6
TOTAL SCORE		19	58	21	67	16	49

Table 14: Al-Shuaibah, Bin Asmad, and Al-Hayer score sheet (Reduced)

Site		**Al-Shuaibah**		**Bin Asmad**		**Al-Hayer**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	2	8	3	12	1	4
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	3	6	3	6
Depth to Water Level (m)	3	2	6	3	9	3	9
TOTAL SCORE		17	51	18	56	16	48

Table 15: Nahel, Alajban, and Sweihan score sheet (Reduced)

Site		**Nahel**		**Alajban**		**Sweihan**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	1	4	2	8
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	4	8	4	8
Depth to Water Level (m)	3	3	9	4	12	3	9
TOTAL SCORE		18	56	18	53	18	54

Table 16: Abu Karrayah, Al Araad, and Al-Wagan score sheet (Reduced)

Site		**Abu Karrayah**		**Al-Araad**		**Wagan**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	1	4	3	12	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	2	6
Groundwater Salinity	4	2	8	2	8	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	4	8	4	8	3	6
Depth to Water Level (m)	3	4	12	2	6	2	6
TOTAL SCORE		18	53	18	55	17	53

Table 17: Ayn Al Fayda, Al-Bateen, and Al-Shuwaib score sheet (Reduced)

Site		**Ayn Al-Fayda**		**Al-Bateen**		**Al-Shuwaib**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	4	12	2	6
Groundwater Salinity	4	2	8	2	8	4	16
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	3	6	4	8
Depth to Water Level (m)	3	2	6	3	9	3	9
TOTAL SCORE		17	53	20	62	21	66

Table 18: Al-Khaznah, Al-Saad, and Al-Quaa score sheet (Reduced)

Site		**Al-Khaznah**		**Al-Saad**		**Al-Quaa**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	2	6	4	12
Groundwater Salinity	4	2	8	2	8	1	4
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	4	8	3	6
Depth to Water Level (m)	3	3	9	3	9	3	9
TOTAL SCORE		18	56	19	58	19	58

Table 19: Sayh Al-Hamah, Al-Khrair, and Remah score sheet (Reduced)

Site		**Sayh Al-Hamah**		**Al-Khrair**		**Remah**	
Criteria/Score	Weighting Factor	Score	Total Score	Score	Total Score	Score	Total Score
Thickness of the Aquifer (m)	4	3	12	3	12	3	12
Aquifer confinement	3	3	9	3	9	3	9
Uniformity of hydraulic properties	3	2	6	4	12	2	6
Groundwater Salinity	4	2	8	4	16	2	8
Hydraulic gradient	3	2	6	2	6	2	6
Consolidation (Porous/Non-Fractured)	2	3	6	3	6	3	6
Depth to Water Level (m)	3	2	6	4	12	4	12
TOTAL SCORE		17	53	23	73	19	59

After applying the score procedure on the 21 available sites, the overall all score out of 80 (maximum possible score) will indicate the best location for potential ASR system. The overall scores for the evaluated sites are listed in Table 20 and presented in Figure 28.

Table 20: Overall scores for the 21 re-evaluated sites

S. No.	Site	Overall score	S. No.	Site	Overall score	S. No.	Site	Overall score
1	Al-Khrair	73	8	Al-Saad	58	15	Abu Karrayah	53
2	Al-Dhahir	67	9	Al-Khaznah	56	16	Ayn Al-Fayda	53
3	Al-Shuwaib	66	10	Nahel	56	17	Alajban	53
4	Al Bateen	62	11	Bin Asmad	56	18	Wagan	53
5	Remah	59	12	Al-Araad	55	19	Al-Shuaibah	51
6	Um El-Zumol	58	13	Sweihan	54	20	Abu Huraibah	49
7	Al-Quaa	58	14	Sayh Al-Hamah	53	21	Al-Hayer	48

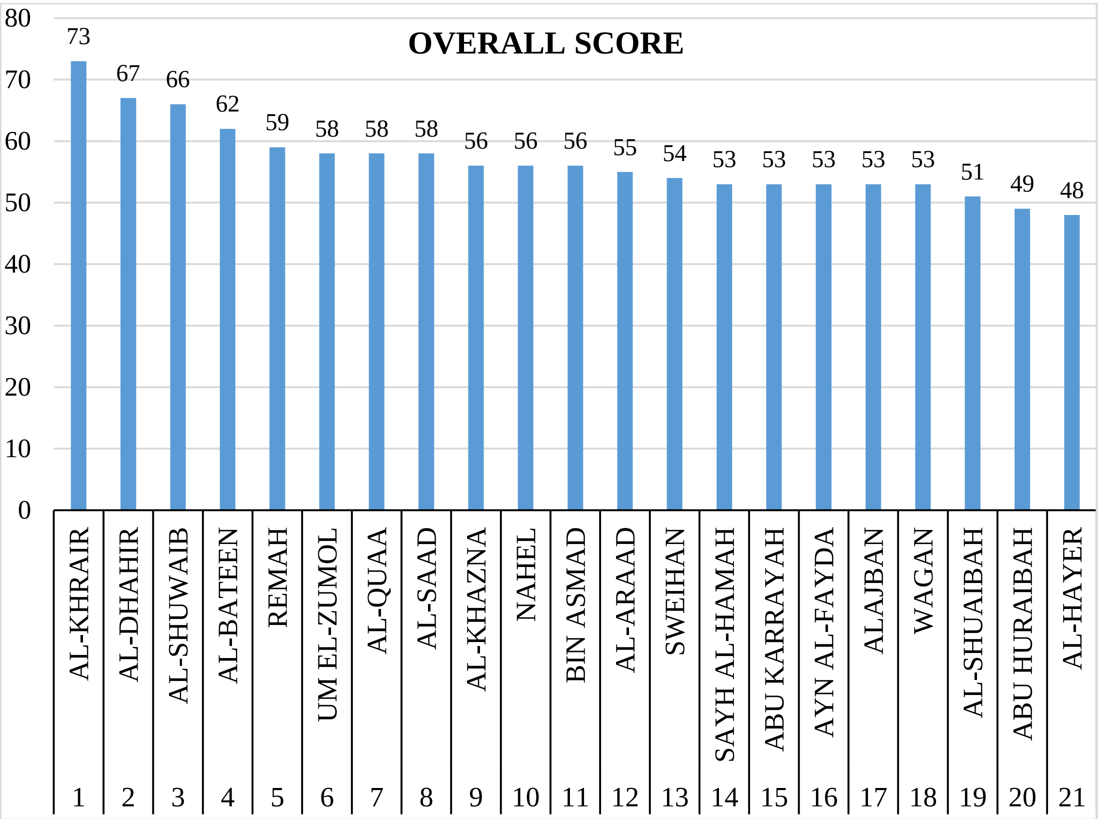


Figure 28: Overall scores for the evaluated sites

As shown in Figure 28, the overall score at the 21 sites are shown in blue bar. The highest score is Al-Khrair site followed by Al-Dhahir and Al-Shuwaib. In both site selection evaluation, the highest scores in the 21 sites are achieved in Al-Khrair site followed by Al-Dhahir, Al-Shuwaib and Al-Bateen sites, respectively.

Figures 29, 30, 31 and 32 present the satellite images of Al-Khrair, Al-Dhahir, and Al-Shuwaib and Al-Bateen locations, respectively.

Figure 29: Satellite image of Al-Khrair site

Figure 30: Satellite image of Al-Dhahir site

Figure 31: Satellite image of Al-Shuwaib site

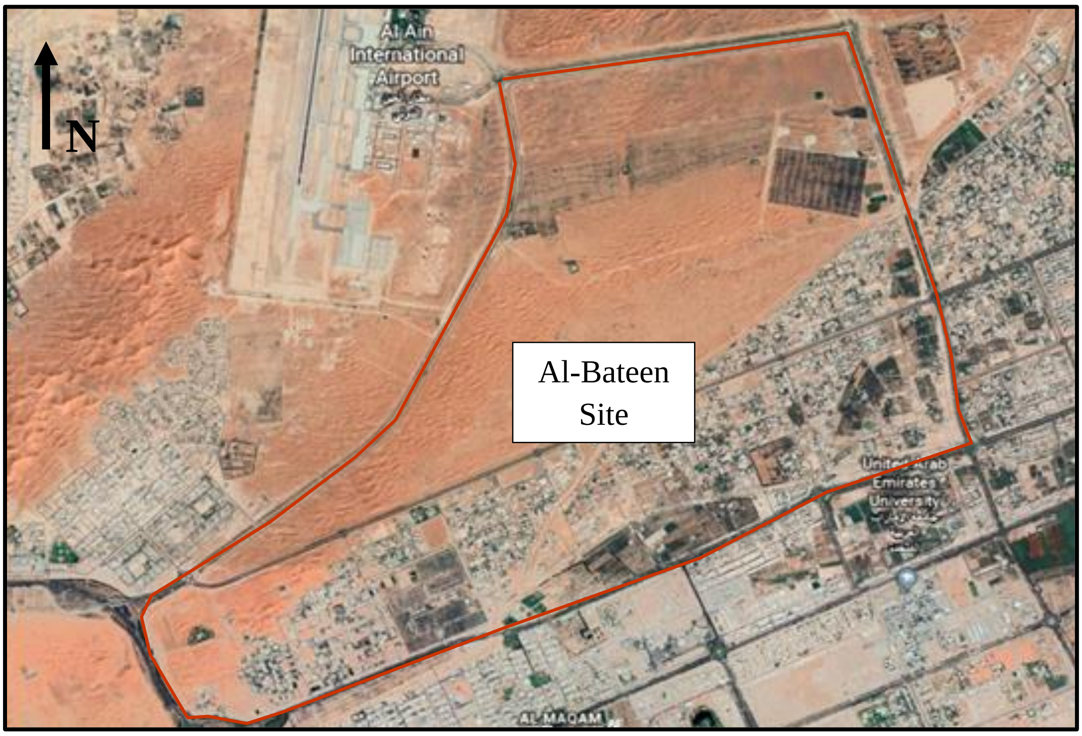


Figure 32: Satellite image of Al-Bateen site

In order to obtain the most favorable location for the ASR project, another criteria was applied to the previous results to minimize the number of the selected sites that will be evaluated for ASR system using the computer model. The criteria is future urbanization and development at the site. Accordingly, Al-Dhahir site is discarded because the site is full of development and urbanization and replaced by Al-Bateen site to be modeled using the computer software.

Chapter 5: Software and Model Development

Visual MODFLOW Flex groundwater modeling software (Visual MODFLOW Flex 2015.1 Software) is the industry standard for simulating groundwater flow and contaminant transport) was used to simulate the groundwater flow in the created conceptual model, simulate stress periods on the flow system and to obtain the water head maps at various recharge rates by injection wells at the selected sites within the study area. The Visual MODFLOW Flex (VMOD) is a powerful software that provides three-dimensional groundwater conceptual and numerical models using imported data, polygons, and object (Waterloo Hydrogeologic, 2012). The finite-difference code was utilized to evaluate the best sites for ASR system and to identify the site's suitability for the implementation of ASR project. The partial differential equation used by VMOD Flex to describe the three-dimensional movement of the groundwater through porous earth media (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W = S_s\frac{\partial h}{\partial t}$$

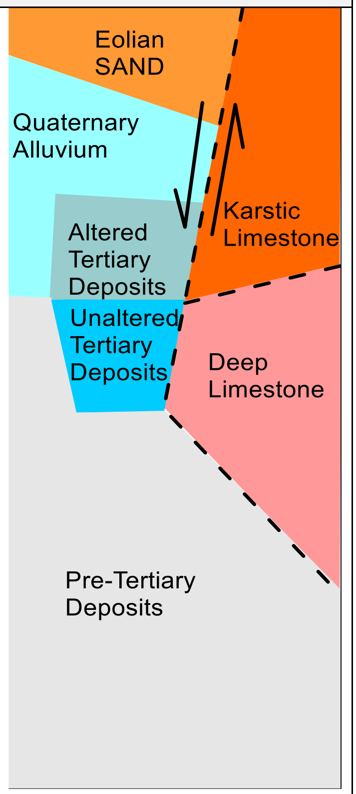
Where K_{xx},K_{yy}, and K_{zz} are the hydraulic conductivity along the x-,y-, z-axes, respectively which are assumed to be parallel to the major axes of hydraulic conductivity (LT^{-1}); h is the groundwater head (L); W is the volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1}); S_s is the specific storage of the porous media (L^{-1}); and t is the time (T).

The first step prior to the simulation is to build a conceptual model of the groundwater system. Defining the property zones (assign property values for conductivity, storage, and initial heads) and boundary conditions are all designed outside the model grid.

5.1 Data Preparation

Three geological layers were reported previously by USGS (Hutchinson, 1998) and (Brook, 2005) namely, surficial aquifer (Sand & Gravel Aquifer), upper Fars Formation, and lower Fars Formation. For this model, as evidenced by hundreds of the boreholes that were drilled by NDC (National Drilling Company) and USGS (United states geological survey) during the 1990s, there is a hydrogeological connection between the bottom of the surficial aquifer and the underlain Upper Fars Formation at the eastern part towards Oman Mountains (Sadhasivam et al., 2018). Therefore, it was modeled that the surficial aquifer layer (unconfined and highly productive quaternary alluvium) and the upper Fars Formation is conceptualized as a one layer overlying the lower Fars Formation which is considered as the bottom of the aquifer or the top of the confining layer (impermeable layer) as shown in Table 21. It is modeled that groundwater recharges in an unconfined aquifer.

Table 21: Hydrogeological framework of eastern Abu Dhabi Emirate (Hutchinson, 1998)

Age	Geologic Sequence	Approximate Thickness (m)	Hydrogeological Unit	
Quaternary	Eolian Sand	25	Unsaturated overburden	
	Alluvium	30	Surficial aquifer system	
Pliocene-Miocene	Post-Fars Upper Fars	200		
Miocene-Oligocene	Lower Fars Formation Asmari Formation	500	Basal Confining unit	
Paleocene-Eocene	Dammam Formation Rus Formation Umm er-radhum	1200		
Cretaceous	Simsima Formation Qahlah Formation Juweiza Formation	3000		

Al-Ain region boundary is obtained using GIS Software, the study area boundary is inserted to the model as a polygon (shapefile) and it is required by VMOD software to create the conceptual model and run the numerical model. Each point on the Map presented in Figure 33 includes data such as recorded water level (m), elevation (m), aquifer thickness (m), and coordinates.

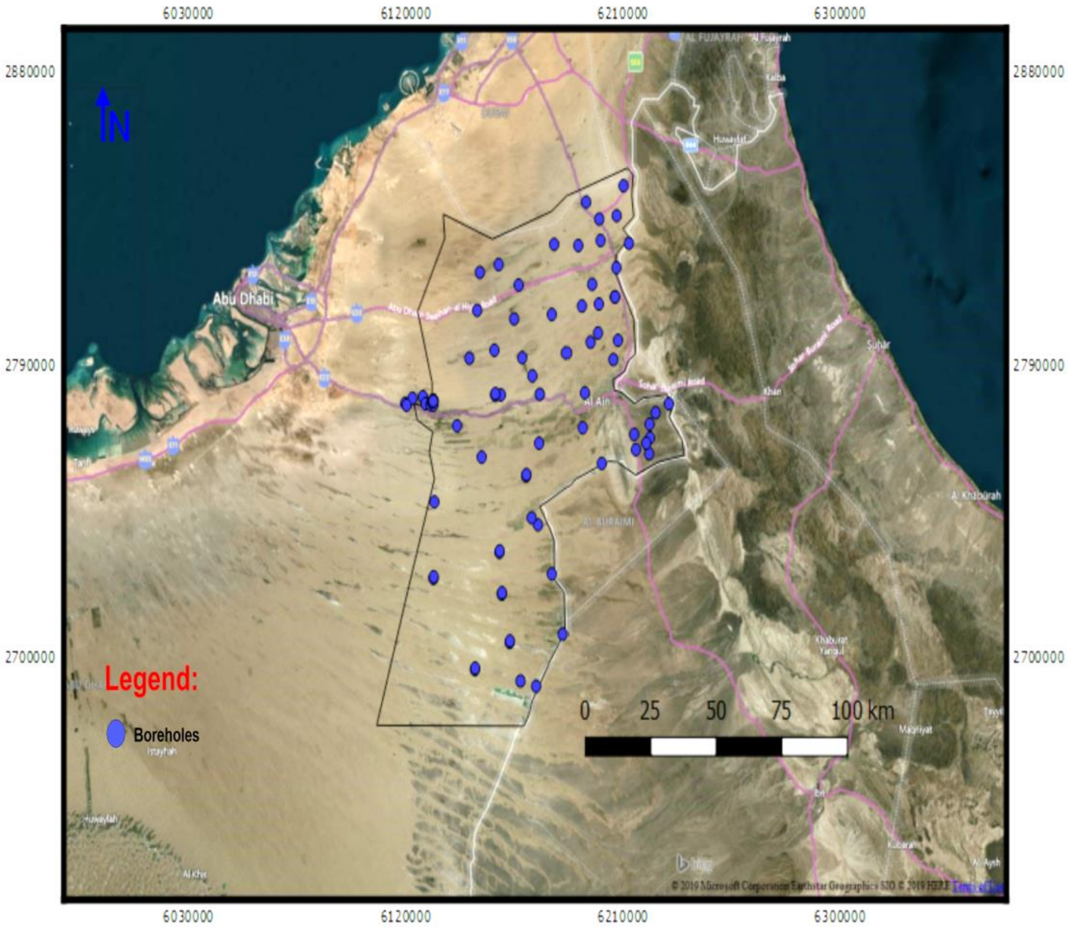


Figure 33: Satellite image of the study area boundary with collected data points

5.2 Conceptual Model

Conceptual Model is the representation of the hydrogeological system being modeled and it is necessary to generate the numerical model. The conceptual model was created using elevation (m), initial water head (m), and bottom of the aquifer (m) data collected from several sources. The created conceptual model for Al-Ain unconfined aquifer is represented in Figure 34.

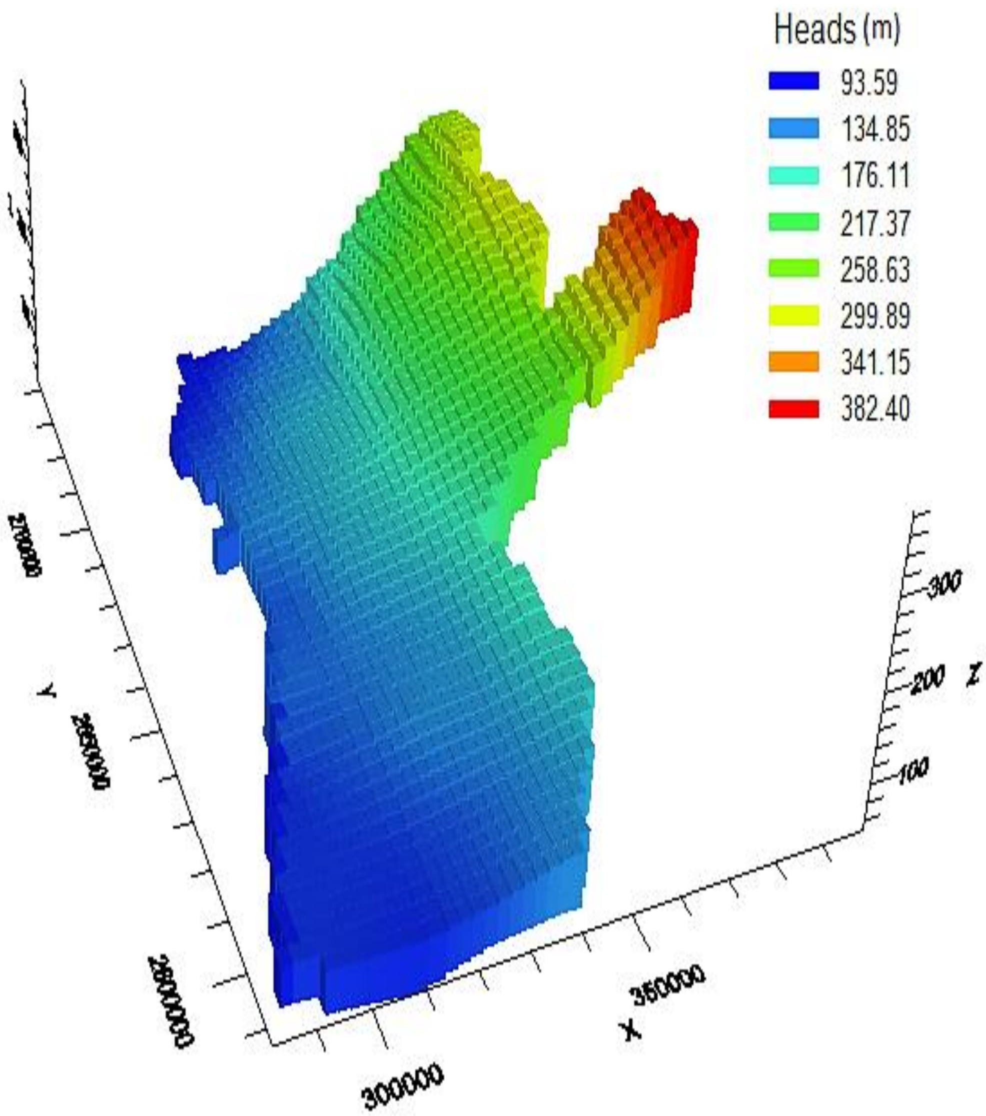


Figure 34: Conceptualization of the Al-Ain region aquifer for regional groundwater model

The configuration, defining the property zones, boundary conditions, groundwater recharge areas, and flow directions are critical steps to create any groundwater flow model. Field data, previous investigations and other data sources provided the hydrogeological data required to create the above conceptual model.

5.3 Defining the Structure

At this step, the geological surfaces that will represents the tops and bottoms of the geological model is provided (Waterloo Hydrogeologic, 2012) to be converted into horizons for conceptual model . The top of the aquifer is represented by topographic data obtained (the ground surface) while the bottom of the aquifer/top of confining layer is obtained from various data of boreholes drilled in the study area from EAD (Environment Agency-Abu Dhabi) and ACES (Arab Center For Engineering Studies Company) as well as data collected from previous thesis (Al Shahi, 2002) which belongs to NDC. The created horizons presented in Figure 35 will be used later in defining properties.

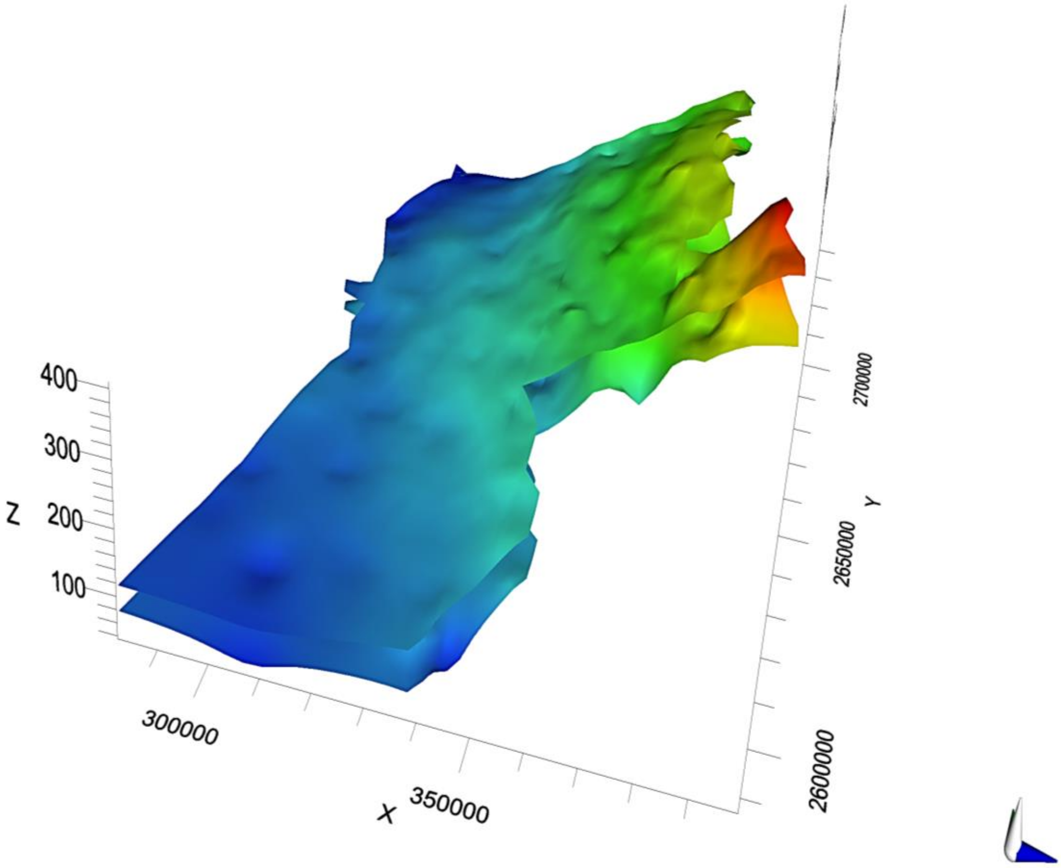


Figure 35: Created horizons in the model

5.4 Defining the Property zone

One property zone is considered to model the study area as presented in Figure 36. The property attributes, e.g. hydraulic conductivity, specific storage, and initial heads were assigned for this zone. The hydraulic conductivity (K) determines the ease with which water to flows through unit of pore spaces or fractures of rock under a certain hydraulic gradient, while the specific yield and specific storage are aquifer parameters that express how much water can be stored and released from the soil or rock (EAD, 2018). The specific yield (S_y) is defined as the ratio of the volume of water that a saturated soil or rock will yield by gravity to the total volume of soil or rock as defined in USGS publication (Johnson, 1967). Total Porosity is defined as the ratio of voids in a soil mass to the total volume of soil mass usually expressed in percentage while effective porosity is the void spaces that will yield water or the connected pores that will contribute to permeability. Effective porosity is typically less than total porosity and it is also known as specific yield (Johnson, 1967).

Hydraulic conductivity (K) can be indicated by the following equation:

$$K = \frac{Q}{(I \; X \; A)}$$

Where: K: Hydraulic conductivity (m/day)
Q: Flow (m^3/day)
I: Hydraulic Gradient
A: Area (m^2)

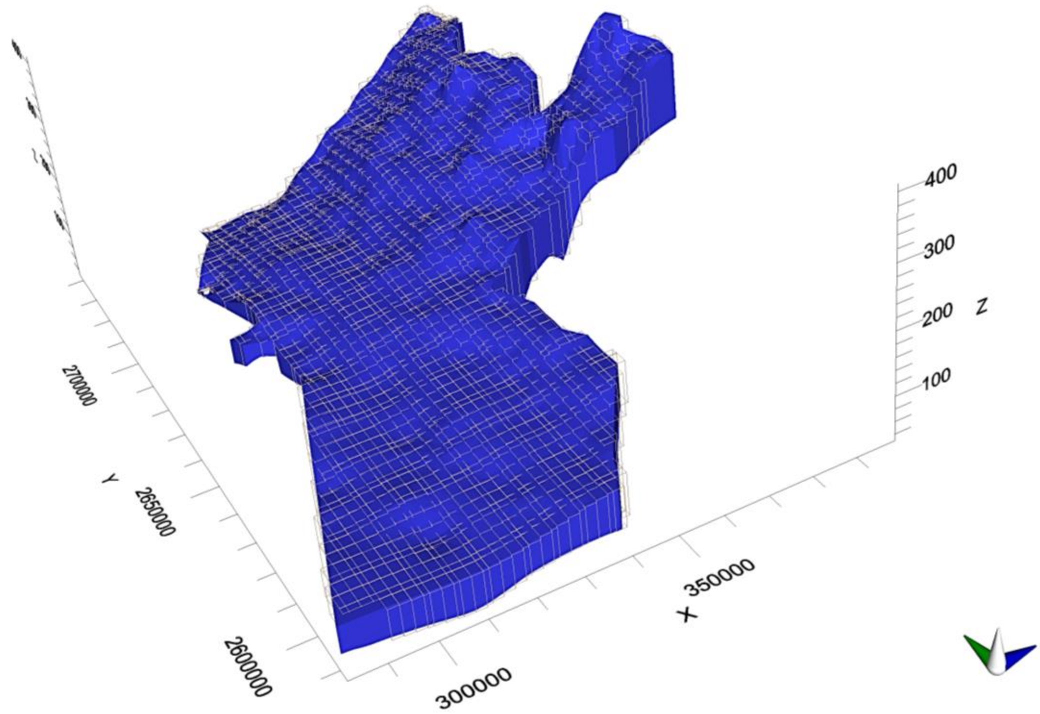


Figure 36: The created property zone

The horizontal and vertical hydraulic conductivity were assigned to the zone based on data collected from previous thesis (Al Shahi, 2002). Forty five (45) points of horizontal hydraulic conductivity distributed over the study area with maximum value of 0.003 m/sec, minimum value of 1.157E-06 m/sec, and average hydraulic conductivity of 0.0002 m/sec were assigned while the vertical hydraulic conductivity is tenth of the horizontal conductivity based on data from Al Shahi (2002).

Initial parameters of specific yield, total porosity, effective porosity, and specific storage were used in the model until a good match achieved between the observed and calculated model parameters. According to several reports and tests conducted in the study area (Al Shahi, 2002; Al Badi, 2003; McDonnel and Fragaszy, 2016; Sadhasivam and Mohamed, 2018), the specific yield measured ranges from 0.01 to 0.27 (Al Shahi, 2002), while it is ranges from 0.02 to 0.18 in the alluvium aquifer as stated by Al Badi (2003) and average specific yield of 0.14 was reported by McDonnel and Fragaszy (2016). In addition, Sadhasivam and Mohamed (2018), used specific yield ranging from 0.01 to 0.32.

A total porosity of 0.4 was assigned as the study area aquifer is characterized by high porosity (Mahgoub, 2008) which also indicates that the study area is appropriate of ASR site selection (Al-Katheeri, 2007). However, a sensitivity analysis for all previous property attributes was developed after several trials of different aquifer parameters in order to achieve the best results and understood the uncertainty in the aquifer parameters.

5.5 Grid Design and Boundary Conditions

The entire model domain area is around 18,207 Km^2 while the horizontal extent of the modeled area is ranging between UTM coordinates 282061E to 399020E in x-direction (Easting) and 2586967N to 2742639N in y-direction (Northing) as presented in Figure 37**.** The size of the grid has a major role in terms of accuracy of the model outputs (Sadhasivam and Mohamed, 2018)**.**

5.5.1 Grid Design and Discretization

The areal extent of the study area was examined initially by several uniform grid systems of 20 x 20, 40 x 40, 60 x 60, 80 x 80, and 100 x 100. Twenty one (21) locations within the model were selected to measure the error between the obtained water heads as shown in Figure 37. Furthermore, a threshold value of less than 0.5 average error was set to select the best grid size. Accordingly, the average error between every consecutive grid were calculated and the lowest value is 0.24 for grid size 100 x 100 as presented in Table 22.

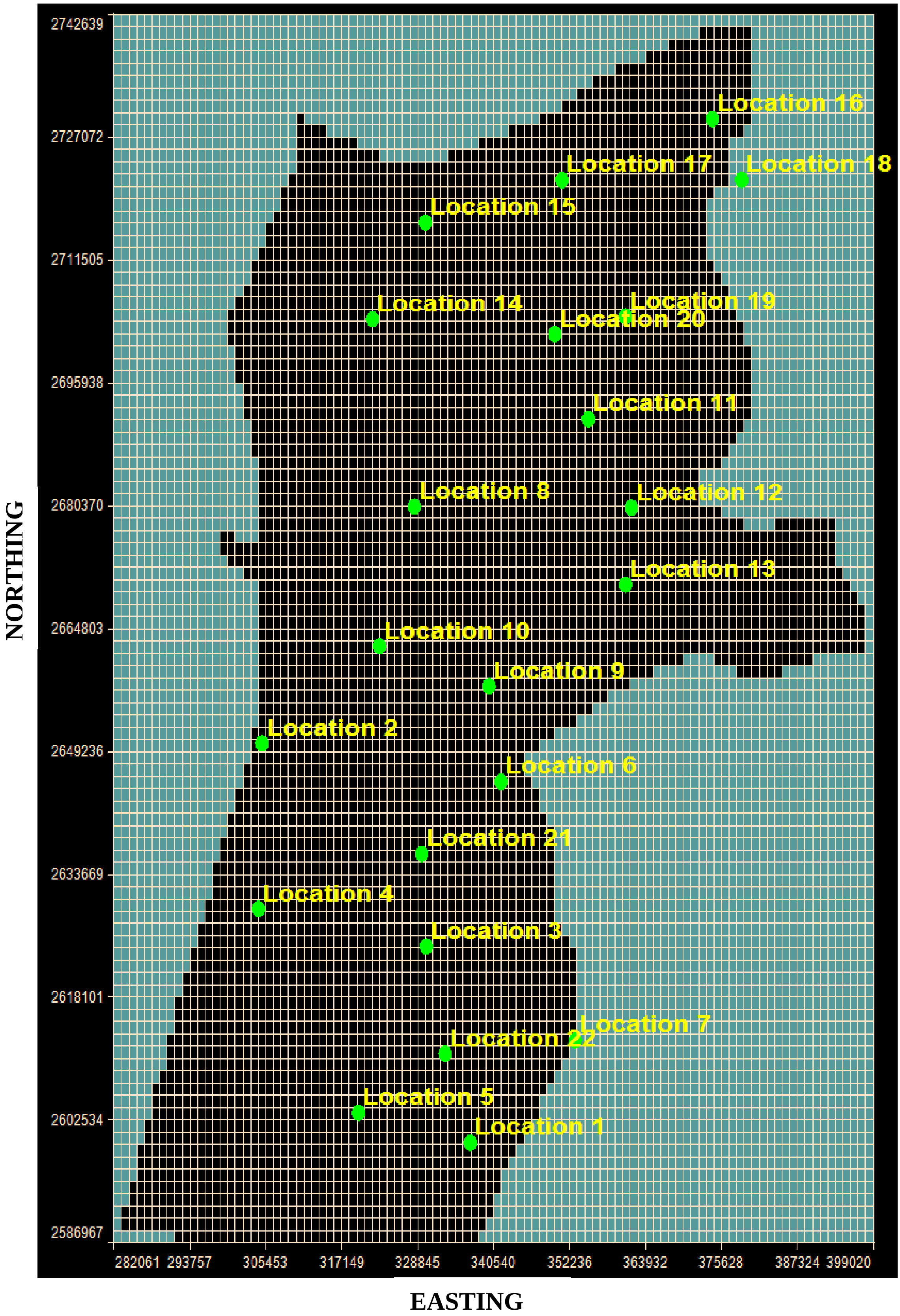


Figure 37: The 21 locations used for selecting the grid size

Table 22: Grid sizes with its computed error

Location	Coordinates		Grid Size								
			20X20	40X40	Error	60X60	Error	80X80	Error	100X100	Error
Location 1	EASTING	336962.902	170.544	170.075	0.28	174.283	2.41	173.022	0.73	172.29	0.42
	NORTHING	2599670.28									
Location 2	EASTING	304866.773	INACTIVE	150	-	150	0.00	150	0.00	151.994	1.31
	NORTHING	2650276.57									
Location 3	EASTING	330191.852	176.048	175.073	0.56	180.148	2.82	178.405	0.98	178.265	0.08
	NORTHING	2624504.45									
Location 4	EASTING	304331.760	150	154.661	3.01	156.356	1.08	156.707	0.22	155.814	0.57
	NORTHING	2629296.53									
Location 5	EASTING	319744.846	165.325	164.23	0.67	168.069	2.28	166.798	0.76	166.157	0.39
	NORTHING	2603478.32									
Location 6	EASTING	341689.966	204.559	202.023	1.26	207.211	2.50	201.799	2.68	201.537	0.13
	NORTHING	2645391.60									
Location 7	EASTING	353119.979	INACTIVE	INACTIVE	-	INACTIVE	-	180.528	-	179.171	0.76
	NORTHING	2612645.31									
Location 8	EASTING	328348.919	209.989	202.387	3.76	217.777	7.07	211.835	2.81	209.548	1.09
	NORTHING	2680263.79									
Location 9	EASTING	339838.927	218.723	213.776	2.31	225.877	5.36	221.347	2.05	218.379	1.36
	NORTHING	2657500.60									
Location 10	EASTING	322953.882	185.961	186.186	0.12	199.38	6.62	193.016	3.30	191.926	0.57
	NORTHING	2662589.63									
Location 11	EASTING	355148.058	257.044	246.042	4.47	265.334	7.27	259.537	2.23	256.529	1.17
	NORTHING	2691344.74									
Location 12	EASTING	361770.131	268.336	267.682	0.24	276.899	3.33	275.877	0.37	272.232	1.34
	NORTHING	2680130.72									
Location 13	EASTING	360858.104	274.683	261.48	5.05	281.468	7.10	275.367	2.22	273.865	0.55
	NORTHING	2670380.71									
Location 14	EASTING	321891.944	209.684	197.371	6.24	209.881	5.96	207.028	1.38	203.01	1.98
	NORTHING	2704014.88									
Location 15	EASTING	330054.009	228.63	214.963	6.36	227.19	5.38	224.52	1.19	223.672	0.38
	NORTHING	2716273.92									
Location 16	EASTING	374229.222	285.057	282.532	0.89	302.37	6.56	302.913	0.18	298.053	1.63
	NORTHING	2729414.97									
Location 17	EASTING	351046.070	252.699	246.841	2.37	264.488	6.67	263.41	0.41	256.806	2.57
	NORTHING	2721654.99									
Location 18	EASTING	378761.196	291.698	INACTIVE	-	INACTIVE	-	INACTIVE	-	INACTIVE	-
	NORTHING	2721699.96									
Location 19	EASTING	360861.130	265.555	255.419	3.97	275.849	7.41	271.197	1.72	267.197	1.50
	NORTHING	2704377.84									
Location 20	EASTING	349965.081	249.379	242.461	2.85	256.889	5.62	254.36	0.99	250.238	1.65
	NORTHING	2702120.81									
Location 21	EASTING	329469.847	186.162	181.827	2.38	185.318	1.88	144.277	28.45	184.147	21.65
	NORTHING	2636260.48									
Average Error			-	-	2.25	-	4.6	-	2.73	-	0.24

Thus, the shallow unconfined aquifer in the study area was modeled using a finite-difference and discretized into a grid system of 100 rows and 100 columns (matrix of 10,000 grid cells) in order to define the numerical grid. Each square within the grid is referred to as a cell. The entire model domain area is 18,207,389,460 m^2 while the study area is around (13,000 km^2). The dimensions of the cell are 1169.595 meters width and 1556.726 meters height, each cell represented a surface area of around 1,820,739 m^2. The numerical grid design of the model is presented in Figure 38.

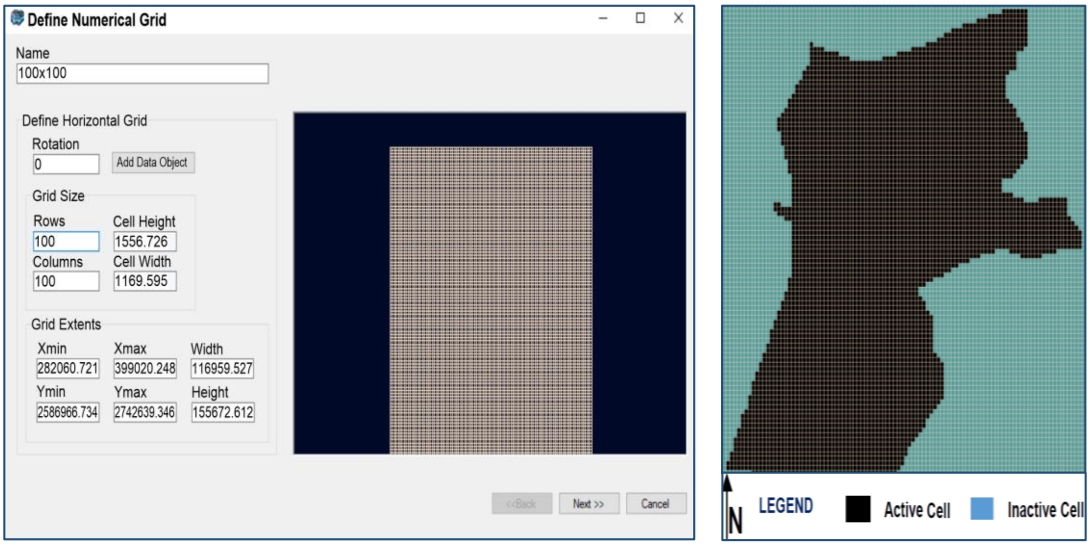


Figure 38: Numerical grid design of the model

5.5.2 Boundary Conditions

Three types of boundary conditions were used in the study model, namely no flow boundary, constant head boundary, and specified flux boundary as shown in Figure 39. As previously discussed in chapter 3, the regional groundwater flow system discharge into the coastal areas moving from eastern boundary of the study area towards the Arabian Gulf. Thus, the northern and southern boundaries of the study area were assigned as no flow boundary condition (hydraulic no flow boundaries running along the East-West direction).

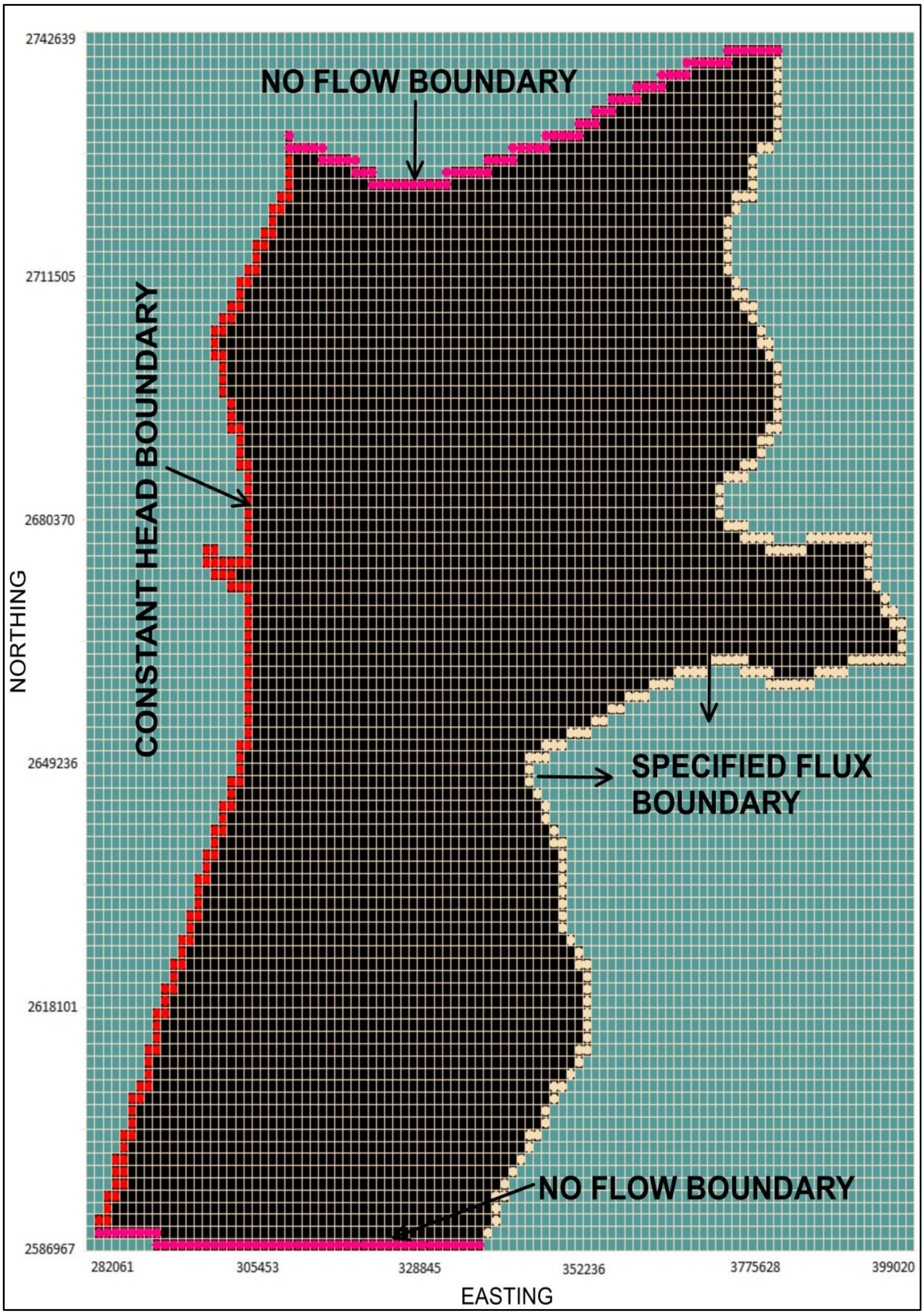
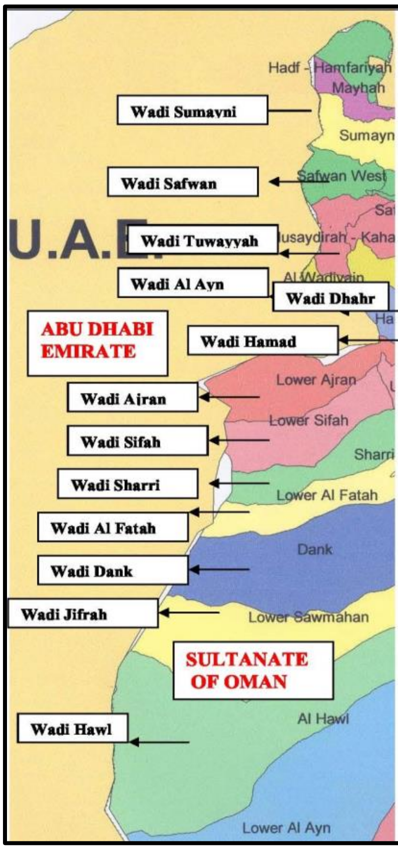


Figure 39: Assigned boundary conditions in the model

Constant head boundary was used to represent the natural discharge from the groundwater flow system to the west of the study area (No change in water level can occur at the constant head cells). Constant, transient specified flux was used at the east boundary of the study area to represent the recharge from Oman Mountain and wadis to the groundwater flow system. The transient specific fluxes from the eastern boundary of the model were assigned based on catchment flow to UAE-Abu Dhabi Emirate (Mm^3/year) as stated by Brook (2005), that the recharge from Oman Mountains is estimated around 30.9 Mm^3/year of water that flow with different degree through groundwater from twelve catchments bounded the eastern boundary of the study area (Brook, 2005) as presented in Figure 40.



Catchment Flow to UAE–Abu Dhabi Emirate (Mm^3/yr)

Catchment	surface	groundwater
Sumayni	0.2	1.4
Safwan	1.48	2.6
Musaydirah – Kahal	1.4	1.9
Al Wadiyain	0.6	4.7
Hamad	1.9	1.1
Ajran	0.0	1.0
Sifah	0.0	2.6
Sharri	0.0	2.4
Al Fatah	2.1	2.0
Dank	0.0	7.0
Sawmahan	0.0	2.6
Al Hawl	0.0	1.6

TOTAL 7.6 Mm^3/yr Wadi Flow

30.9Mm^3/yr Groundwater Throughflow

Figure 40: Major wadi catchments entering the study area from Sultanate of Oman (Brook, 2005)

The constant head implemented at the west of the study area were obtained using a previously observed map (EAD, 2011d). In order to get a value of the constant head boundary condition, the study area boarders (polygon) was superimposed with the observed map as presented in Figure 41.

Due to the irregular shape of the western boarder of the study area, an average constant head value of 110 m above sea level was used to define the constant head boundary condition. The constant head boundary ranges from 100 m to 120 m based on previous map.

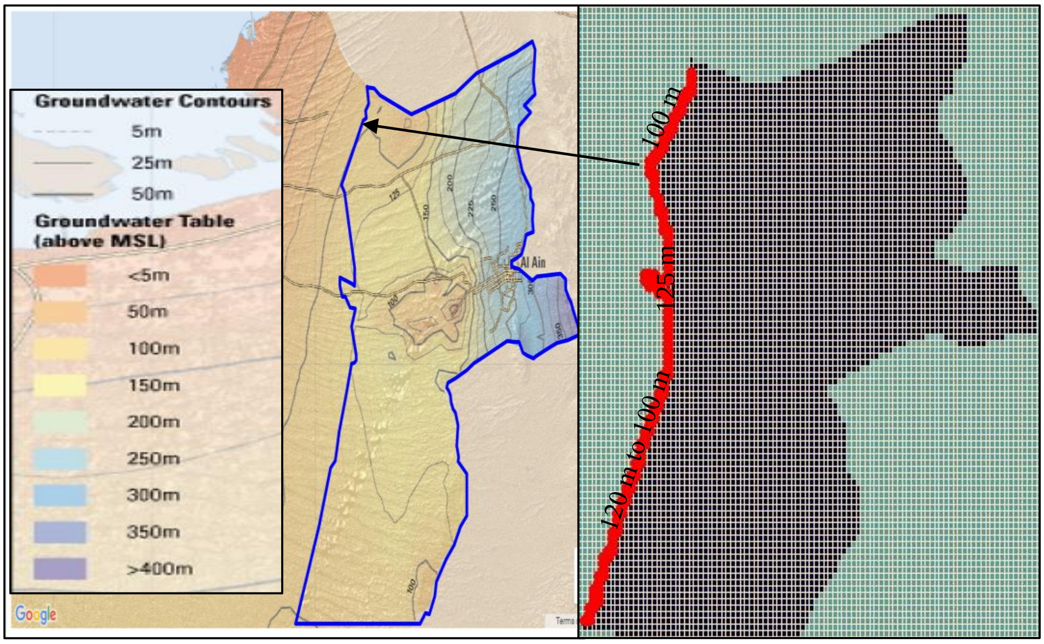


Figure 41: Observed water level map of Abu Dhabi Emirate with study area borders (adopted from EAD, 2011d)

5.6 Model Calibration

The purpose of model calibration is to create a useful and reliable groundwater model (Zhou and Li, 2011). Calibration of a groundwater flow model (model fitting) is the process which follow model design and construction and it aims to identify the best model parameters such as boundary conditions and aquifer parameters that will closely matches the actual field measurements of hydraulic head, water table, and drawdown (Merz and National Centre for Groundwater Research and Training, 2012; Mohamed Haroon, 2004; Othman, 2005). This process is considered as a time consuming and critical stage in any modeling task and it is very important to be implemented in groundwater modeling (Anderson et al., 2015). In this model, manual calibration technique was implemented which is still favorable for majority of users rather than the recent technique known as automated calibration (PEST) which is a code developed for MODFLOW for parameter estimation (Mohamed Haroon, 2004).

For calibration purposes, Visual MODFLOW Flex was set up to run from 1st of January 2013. This date was chosen based on the availability of the data. Observation wells data distributed all over the model domain obtained from Environment Agency - Abu Dhabi (EAD) and Arab Center for Engineering Studies (ACES) enabled the calibration of 18 stress periods (i.e. all model stress such as boundary conditions and recharge in the system remain constant) from 2013 to 2017 (Waterloo Hydrogeologic, 2012). The obtained observation wells data are presented in Figure 42.

After several trial-and-error runs and adjustment of aquifers parameters in order to reduce the difference between observed and calculated hydraulic heads (Sadhasivam et al., 2018), the calibrated aquifer parameters used in the model are uniformed specific yield of 0.14, total porosity of 0.4, effective porosity of 0.25 and specific storage 0.009 (1/m) which were assigned to the model in all the stages of ASR sites selection. A sensitivity analysis was performed on the calibrated aquifers parameters to examine the uncertainty in the model.

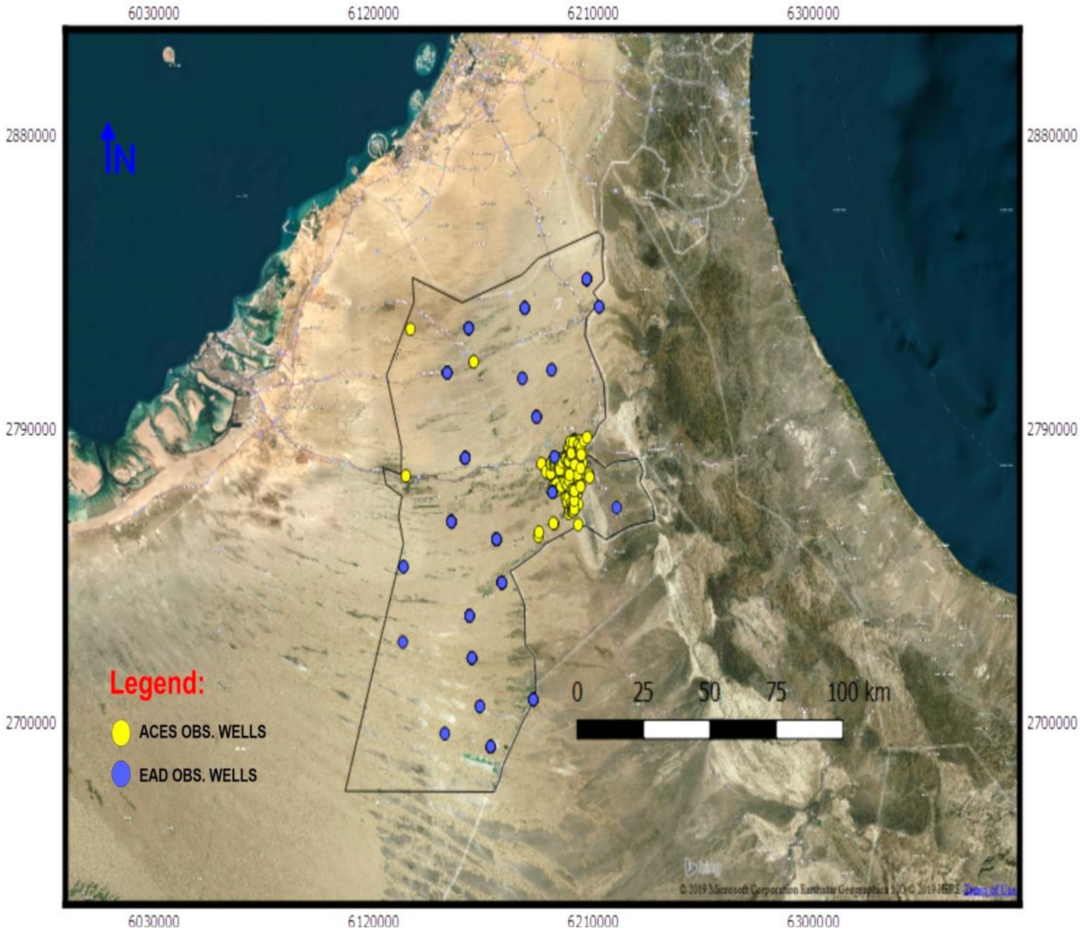


Figure 42: Obtained observation wells data

Calibration chart for each year from 2013 to 2017 were created for EAD and ACES observations wells. In addition, Figure 43 presents a statistical analysis of all observation wells which gives an indication of the performance of the model. The closer the data points are to the 1:1 line, the better the performance of the model (Jovanovic et al., 2017) and prediction accuracy. Model performance and predications are high and reliable when the statistical values (residuals, standard error of the estimates, and root mean squares error) in the bottom of the chart are lower. Furthermore, the correlation coefficient gives an indication of the fit between the calculated and observed values. A good fit can be achieved when the correlation coefficient is closer to 1. In Figure 43, the correlation coefficient is 0.99 which is very near to 1 which indicates that the groundwater levels were simulated well by the model while the standard error of the estimate is 0.51. Root mean square error and Normalized RMS are 12.85 (m) and 6.53%, respectively. The statistical analyses are expected to reduce further if the average groundwater pumping for desert greenery activities was included to the model which estimated around 3.29 MCM/year of every Km^2. However, the uniform desert greenery and average pumping rate noticed in the recent decade (from 2013) as stated by Sadhasivam et al. (2018), was the reason not to consider the desert greenery which is mainly towards the west of the study area in the model (Sadhasivam et al., 2018).

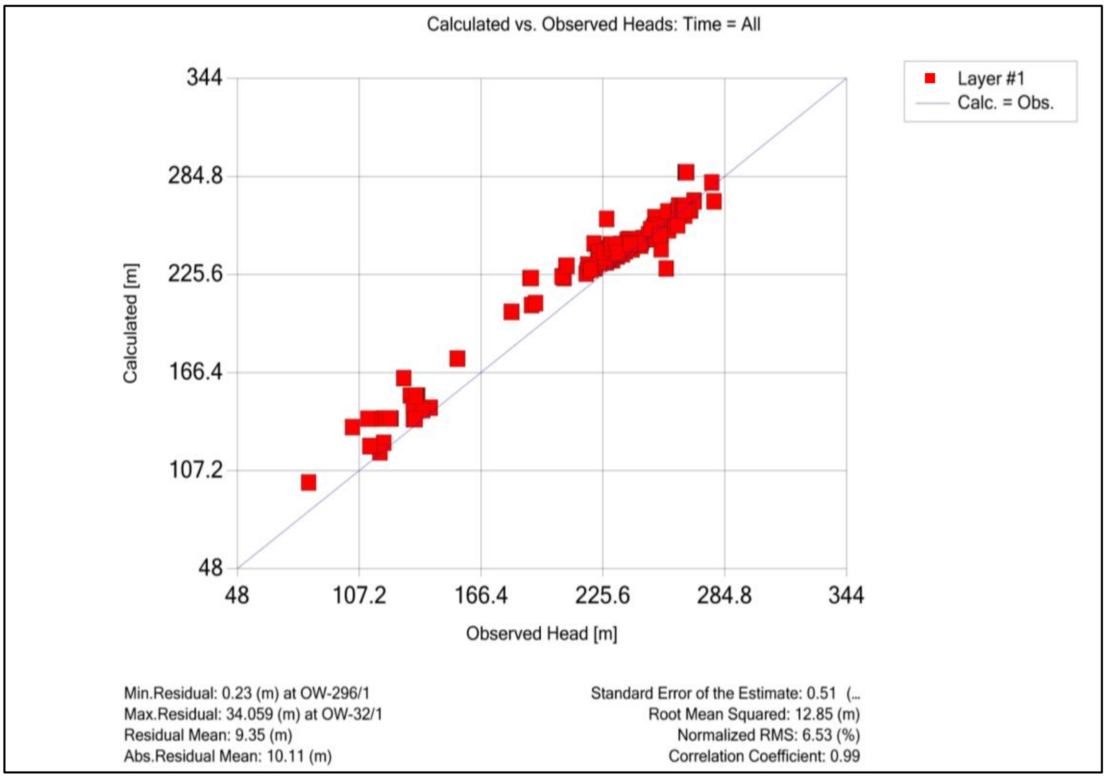


Figure 43: VMOD output calibration chart of calculated groundwater levels versus and observed groundwater levels for all observation wells from 2013 to 2017

Modflow output calibration charts were created for each year individually for EAD (2013, 2014, 2015, and 2017) and ACES (2014, 2015, and 2016) observation wells. The reason of not compiling the similar year of observation wells is that ACES observation boreholes mostly concentrated in the center of Al-Ain region while EAD wells are spatially distributed over the entire study area (mainly away from the center of Al-Ain region) as presented in Figure 42. The VMOD output calibration results for EAD are presented in Figure 43 while ACES calibration results are presented in Figure 44.

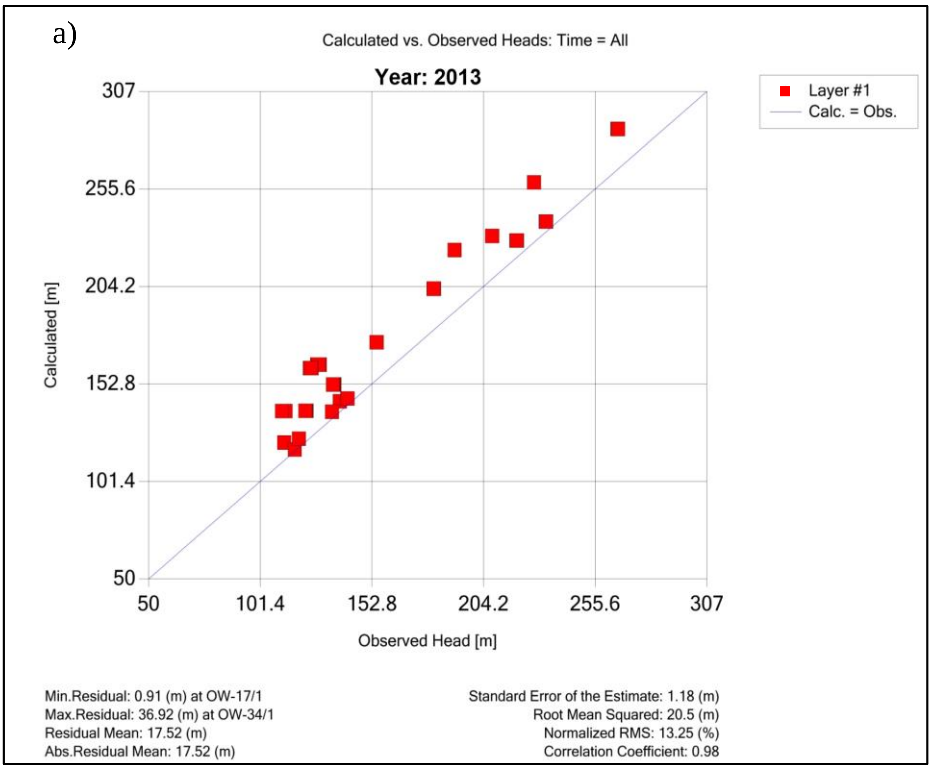
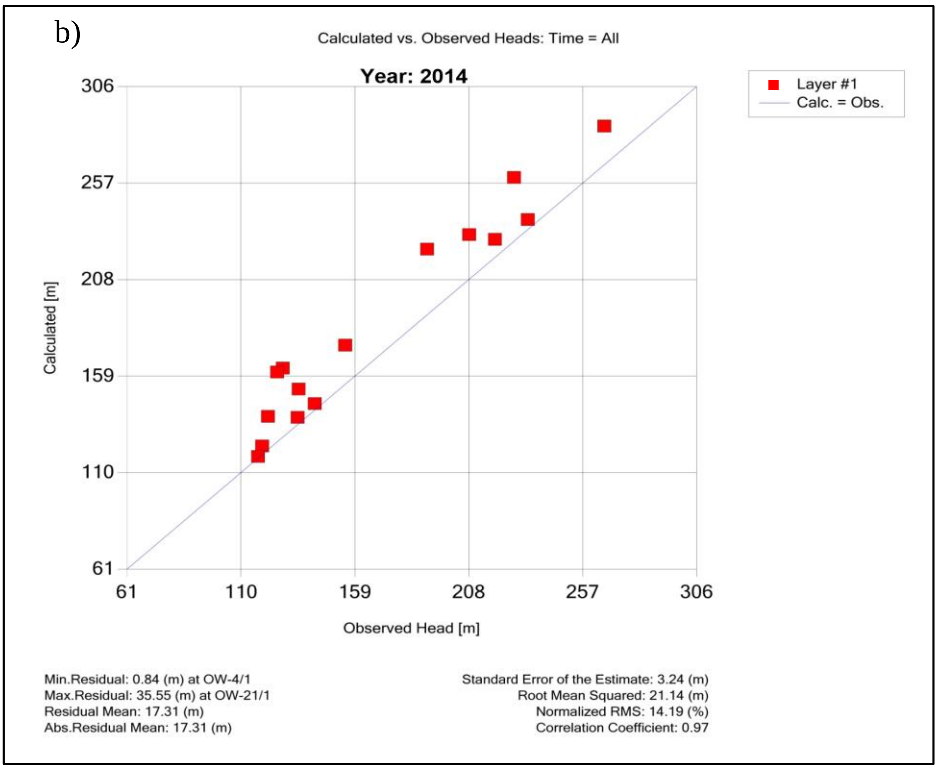


Figure 44: Calculated versus observed calibration chart for a) 2013, b) 2014, c) 2015, and d) 2017 EAD observation wells



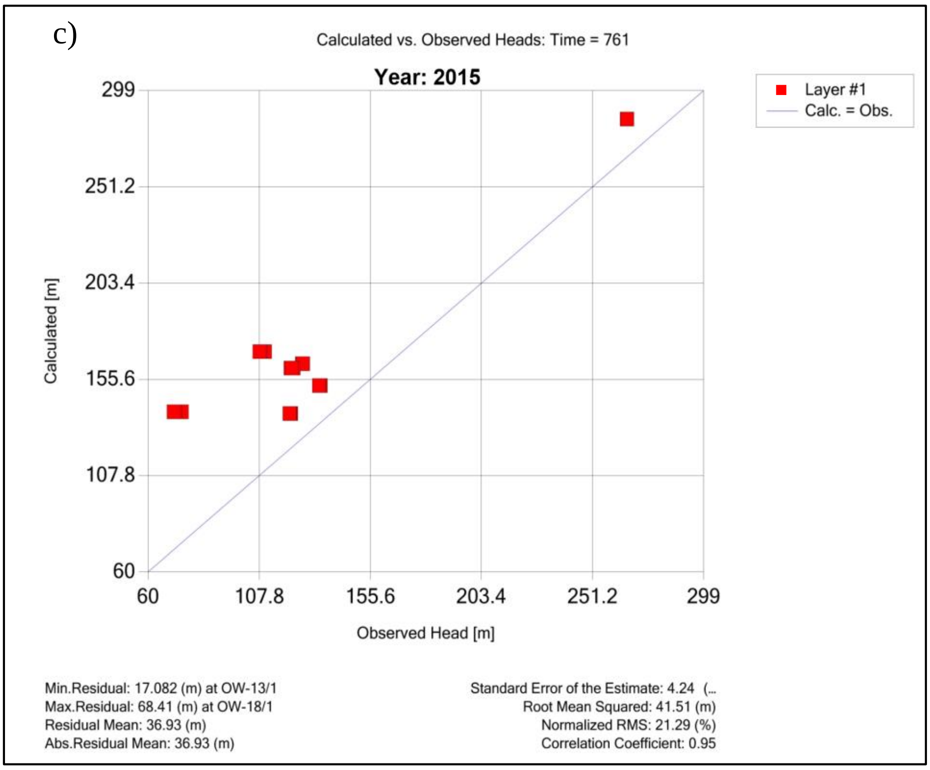


Figure 44: Calculated versus observed calibration chart for a) 2013, b) 2014, c) 2015, and d) 2017 EAD observation wells (Continued)

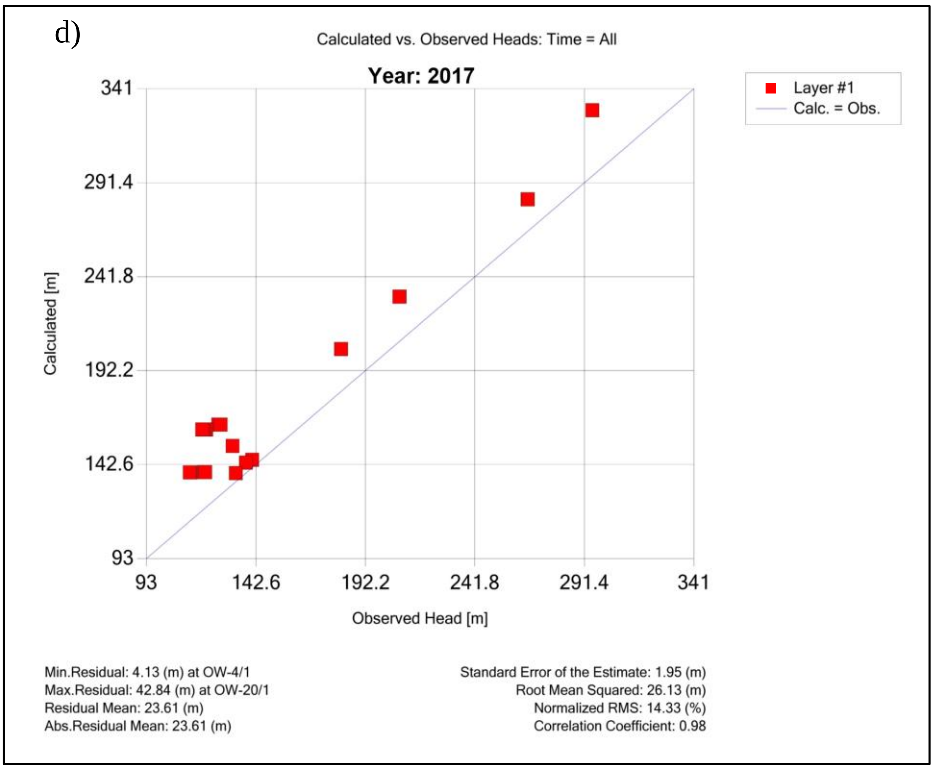
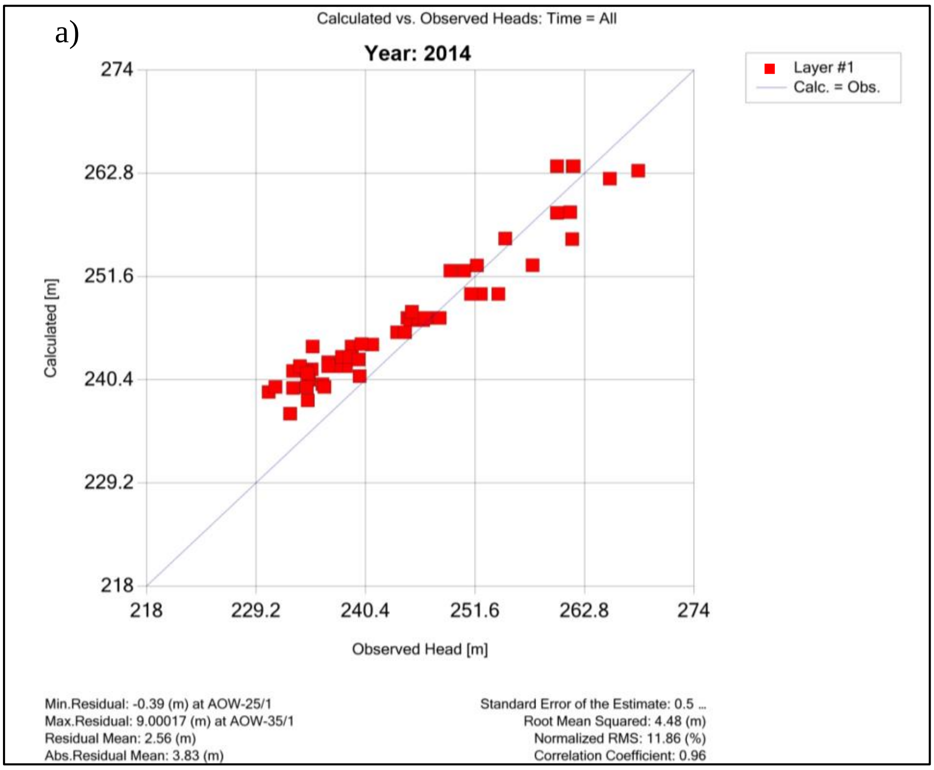


Figure 44: Calculated versus observed calibration chart for a) 2013, b) 2014, c) 2015, and d) 2017 EAD observation wells (Continued)

In Figure 44, the correlation coefficient for years 2013, 2014, 2015, and 2017 is ranging from 0.95 to 0.98 which is near to 1 and indicate that the groundwater levels were simulated well by the model while the Normalized RMS is ranging from 13.25% to 21.29%. The maximum correlation coefficient was achieved in 2014 and 2017 data while the minimum recorded in 2015 with a value of 0.95. The minimum normalized RMS is 13.25% and was achieved in 2014 (the lower the statistical values the better is the model performance). As discussed previously, the statistical values for the calibration charts for EAD wells are assumed to reduce further if the groundwater withdrawals for desert greenery and farms in vicinity of the wells were included in the model.

a)



b)

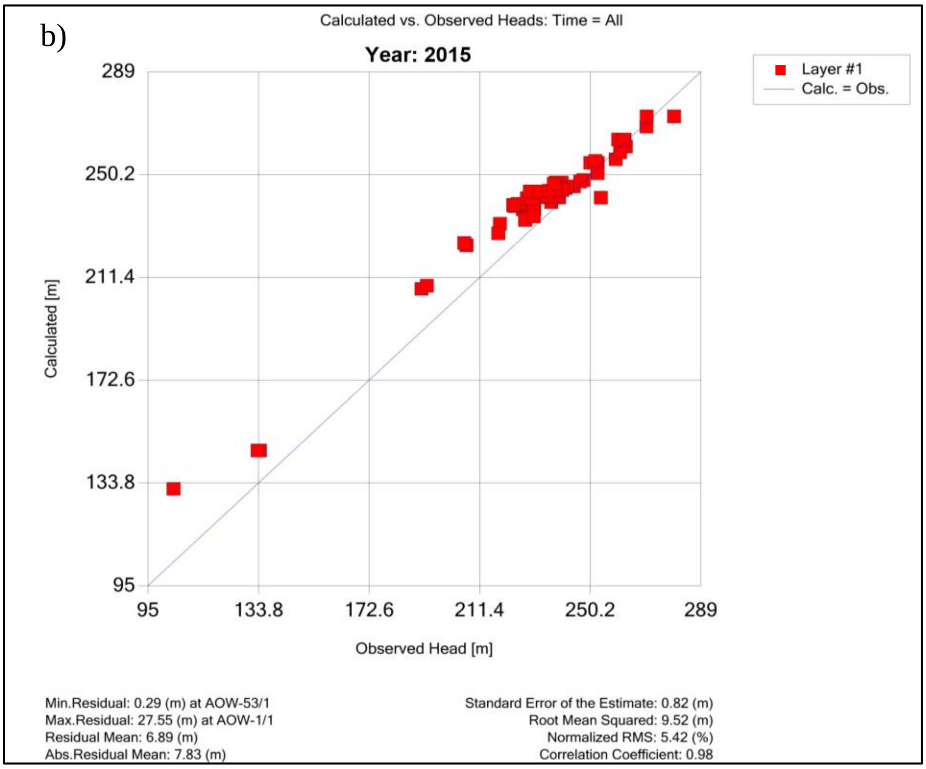


Figure 45: Calculated versus observed calibration chart for a) 2014, b) 2015, and c) 2016 ACES observation wells

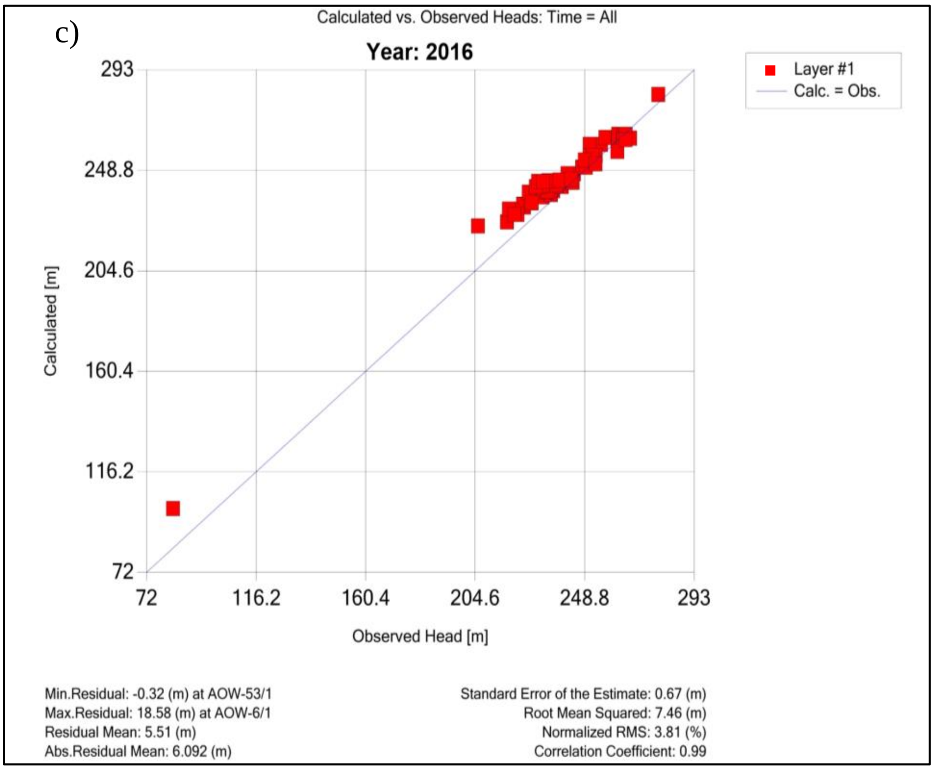


Figure 45: Calculated versus observed calibration chart for a) 2014, b) 2015, and c) 2016 ACES observation wells (Continued)

In Figure 45, the correlation coefficient for years 2014, 2015, and 2016 is ranging from 0.96 to 0.99 which is near to 1 and indicate that the groundwater levels were simulated well by the model while the Normalized RMS is ranging from 3.81% to 11.86% which is almost 50% less than the values achieved in EAD wells. The maximum correlation coefficient was achieved in 2016 data while the minimum recorded in 2014 with a value of 0.96. The minimum normalized RMS is 3.81% and was achieved in 2017. The calibration charts for ACES boreholes indicates better model accuracy and predictions because most of the boreholes are located away from the desert greenery areas and thus showing a well simulated results.

5.7 Sensitivity Analysis

Sensitivity analysis is often the step after calibration of the model and is implemented to examine the robustness of the model to changes in model parameters during the calibration process. In other words, the study of how the system will response to disturbances (Mazzilli et al., 2010). This process is implemented by changing a single model parameter by small amount to check how model outputs will be affected by that change and it is also helpful if implemented in case if the data is not enough to calibrate the model (Merz and National Centre for Groundwater Research and Training, 2012). Accordingly, a sensitivity analysis for all model parameter was developed after several trial-and-error calibration in order to achieve the best results and to understand the uncertainty in the aquifer parameters.

Sensitivity analysis for effective porosity and total porosity were found to be nil sensitivities and have no change in the simulated groundwater head while sensitivity results show that changes in groundwater head were sensitive to changes in specific storage and specific yield as listed in Tables 23 and 24.

Table 23: Sensitivity analysis for specific storage

Run	**Specific storage**	**Specific yield**	**Effective Porosity**	**Total porosity**	**Standard error of estimates**	**Root mean squared**	**Normalized RMS**	**Correlation coefficient**
1	0.001	0.2	0.25	0.4	1.18	20.54	13.28	0.98
2	0.002	0.2	0.25	0.4	1.18	20.52	13.26	0.98
3	0.003	0.2	0.25	0.4	1.18	20.51	13.26	0.98
4	0.004	0.2	0.25	0.4	1.18	20.5	13.26	0.98
5	0.005	0.2	0.25	0.4	1.18	20.5	13.25	0.98
6	0.009	0.2	0.25	0.4	1.17	20.5	13.25	0.98
7	0.01	0.2	0.25	0.4	1.17	20.5	13.25	0.98
8	0.02	0.2	0.25	0.4	1.17	20.5	13.25	0.98
9	0.025	0.2	0.25	0.4	1.17	20.5	13.25	0.98
10	0.03	0.2	0.25	0.4	NOT CONVERGING			

Table 24: Sensitivity analysis for specific yield

Run	Specific storage	Specific yield	Effective Porosity	Total porosity	Standard error of estimates	Root mean squared	Normalized RMS	Correlation coefficient
1	0.009	0.05	0.25	0.4	1.17	20.46	13.23	0.98
2	0.009	0.1	0.25	0.4	1.17	20.49	13.24	0.98
3	0.009	0.2	0.25	0.4	1.17	20.5	13.25	0.98
4	0.009	0.14	0.25	0.4	1.17	20.49	13.25	0.98
5	0.009	0.01	0.25	0.4	NOT CONVERGING			
6	0.009	0.045	0.25	0.3	NOT CONVERGING			

From the tables above, it is clear that no significant changes in model statistical analysis and groundwater level which indicate that the model have a low sensitivity and can be used in further stages (Sadhasivam et al., 2018). Two models were created initially to choose the specific yield of 0.05 or 0.14 and specific storage of 0.01 or 0.009. However, the two models showed typical outputs. Therefore, the average specific yield was chosen to be 0.14 instead of 0.05 (Al Shahi, 2002; McDonnel and Fragaszy, 2016) because this value is considered similar to previous reports and studies in the area while specific storage was chosen to be 0.009 as it showing less statistical results.

Chapter 6: Results and Discussion

The calibrated model was used to evaluate the three selected sites based on the highest score achieved after applying the ASR suitability criteria. The three selected sites are Al-Shuwaib site located north of the study area, Al-Bateen site located in the center of the study area, and Al-Khrair site located in the east of the study area (Al-Jaww Plain).

Many Gulf countries studied the behavior of groundwater flow under specific recharge rate by injection wells. The most recent ASR system was implemented in Liwa, UAE. The full ASR plant construction started in 2009 and completed in 2016. The infiltration of desalinated seawater started in 2015 (Stuyfzand et al., 2017) and aimed to store a surplus of 23 MCM of desalinated water into an aquifer (Klingbeil, 2012).

A summary of the ASR recharge from injection well in different countries is mentioned in chapter 1 while previous ASR pilot tests in UAE (Hutchinson, 1998; Al-Katheeri, 2007; Klingbeil, 2012; Dawoud, 2013, 2014; Stuyfzand et al., 2017) are listed in Table 25.

Table 25**:** Summary of the ASR pilot tests in UAE

Location	**Recharge Rate (m^3/day)**	**Year**
Al-Ain (eastern region)	1,000	1998
Nizwa area (Sharjah)	600-6,000	2003-2004
Liwa (western region)	650-800	2002

The transmissivity of an aquifer, well hydraulics, clogging rate, and availability of water are main factors to decide the rate of injection (Mukhopadhyay et al., 1998).

6.1 Basic Scenarios

The three selected sites were simulated with four water injection scenarios as listed in Table 26. The aim of each scenario is to simulate and understand the groundwater flow behavior under the various rates of recharge from one injection well (Kulkarni, 2015).

Table 26: The simulated water injection scenarios

Scenario	**Injection Rate (m^3/day)**
Scenario I	1,000
Scenario II	2,000
Scenario III	4,000
Scenario IV	8,000

The aquifer thickness in Al-Shuwaib site is around 20 m, in Al-Bateen site is around 18 m while in Al-Khrair site is around 40 m according to the data obtained from EAD and ACES. All of them has a score of 3 which is ‘’good’’ according to the suitability assessment implemented on each site.

Initially, a basic run was generated in a steady state to create the basic run which simulated 1st of January 2013. Transient state runs were simulated for 18 stress periods (18 years) starting from 1st of January 2013 which corresponds to time = 0 until 31st of December 2030 which corresponds to time = 6574. The basic run doesn't include the ASR injection wells at each selected site and was developed to compare the model with the simulated models with assumed water injection scenarios. The basic run water heads (m) result is presented in Figure 46.

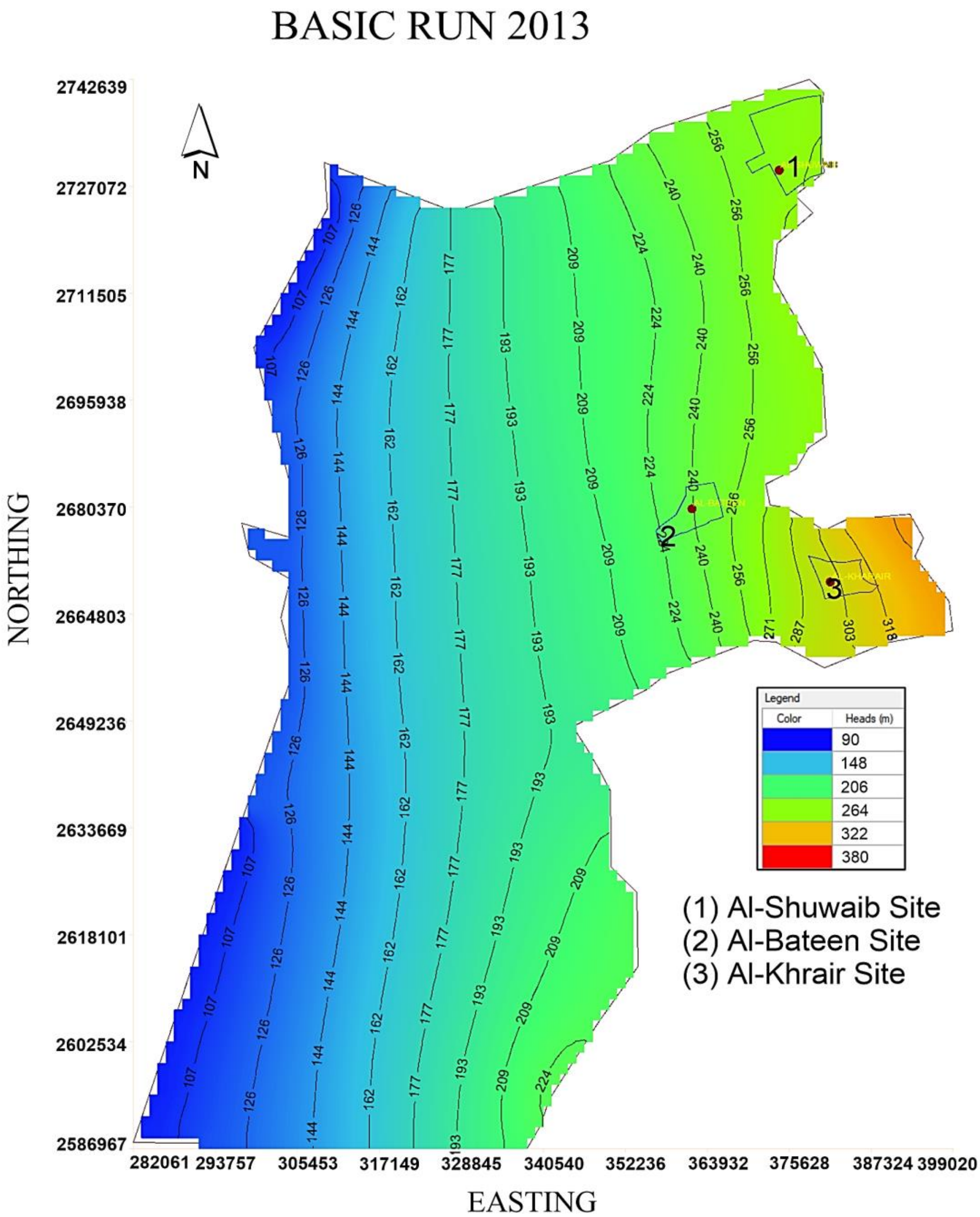


Figure 46: Simulated Basic Run water heads in 2013 result

From the figure above, the hydraulic head (m) is greatest at the eastern part of the study area near to Oman Mountains reaching up to 350 m while the hydraulic head is decreasing towards the west of the study area.

6.1.1 Scenario I (Recharge Rate 1,000 m^3/day)

In this scenario, the model was simulated with water recharge rate of 1,000 m^3/day from year 2013 until 2030 through an injection well located at each selected site. This recharge rate is equivalent to the recharge rate simulated previously in the study area (Hutchinson, 1998). The simulated hydraulic heads increased slightly at the location of the injection well. For Al-Bateen site, the hydraulic head is 242.93 m in 2030 compared to 242.6 m in 2015 and in Al-Shuwaib the hydraulic head is 276.8 in 2030 compared to 275.21 in 2015 while in Al-Khrair site, the hydraulic head is 302.4 m 2030 compared to 301.3 m in 2015. The simulated hydraulic heads for 2015, 2020, 2025, and 2030 are presented in Figure 47.

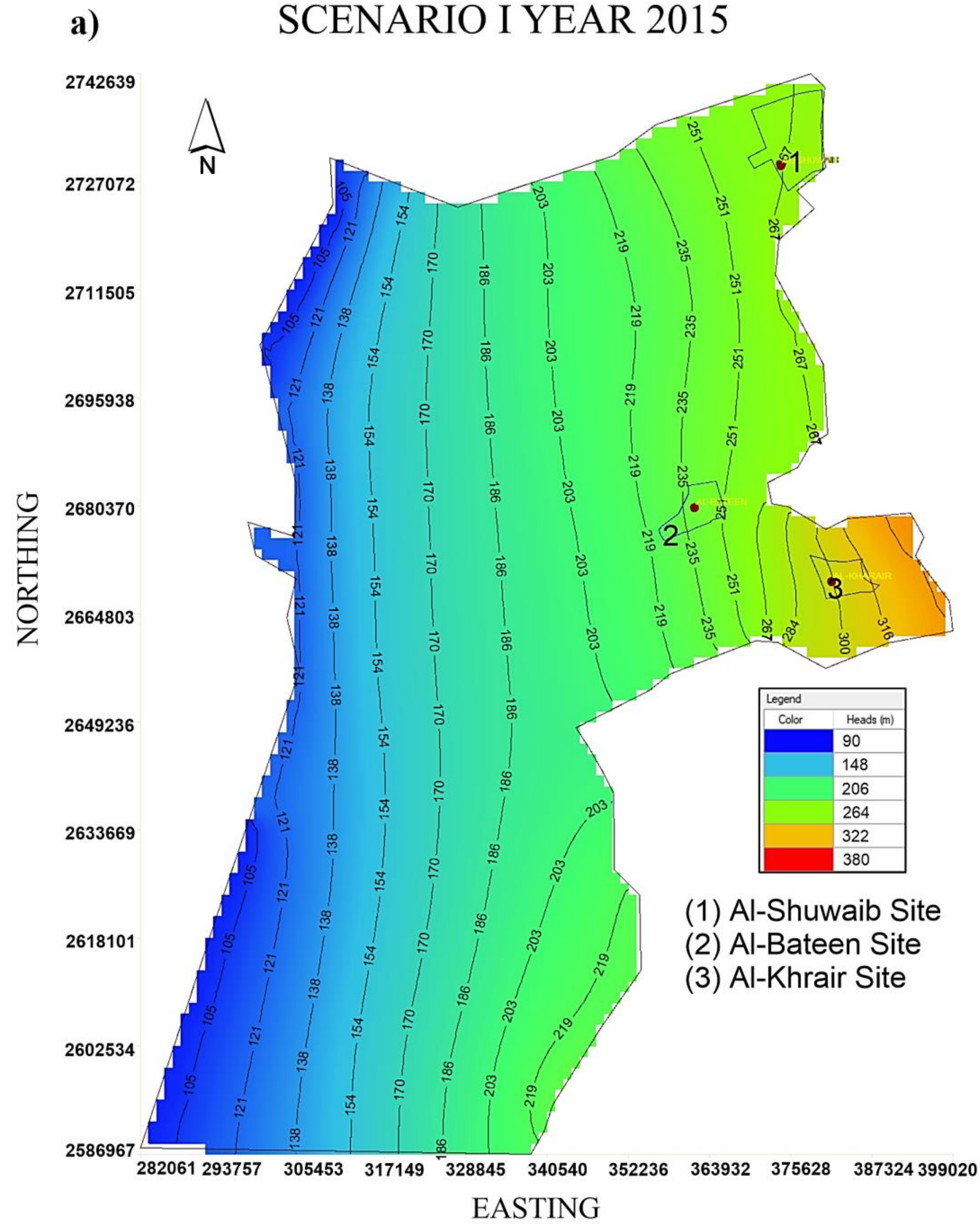


Figure 47: Scenario I simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030

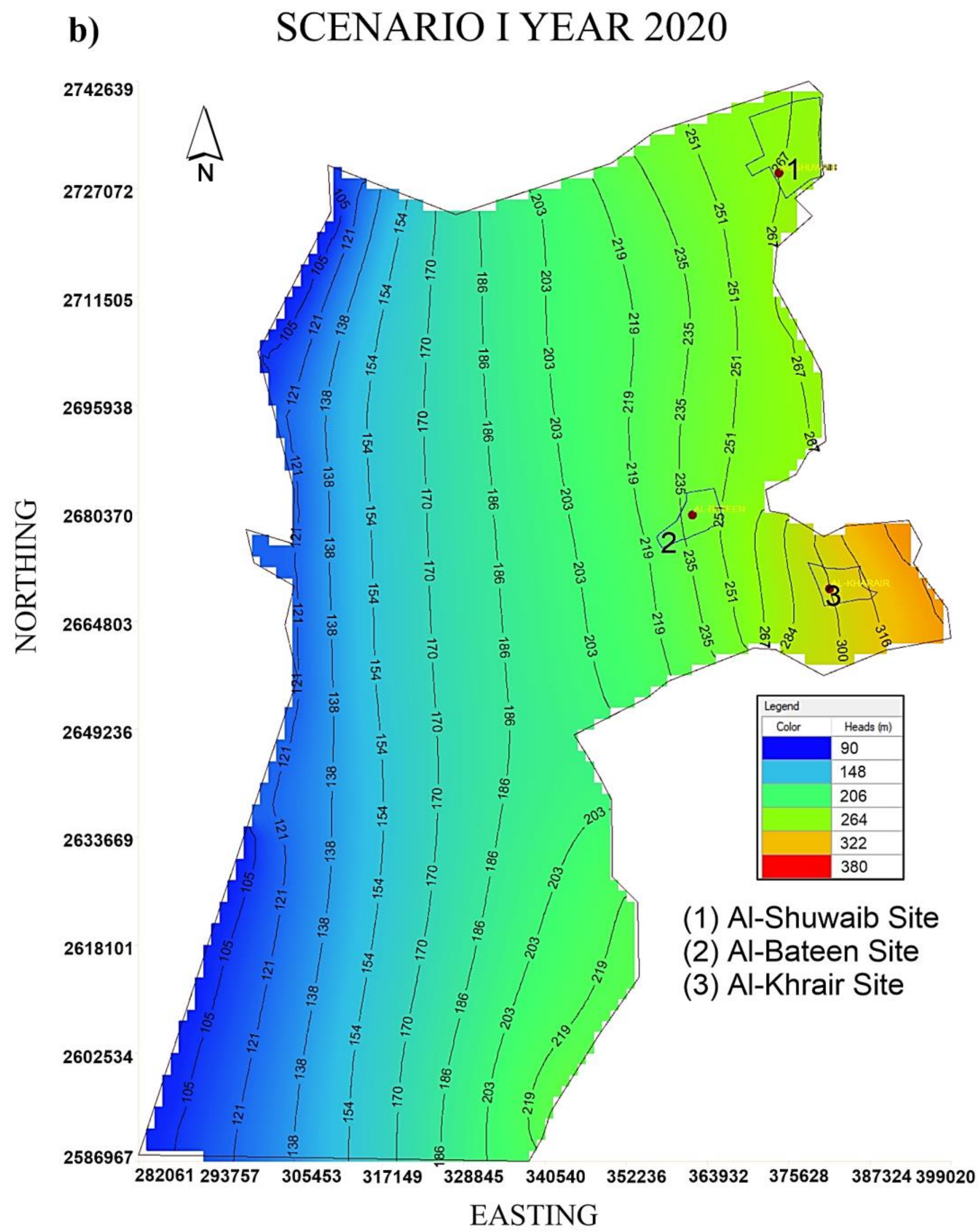


Figure 47: Scenario I simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

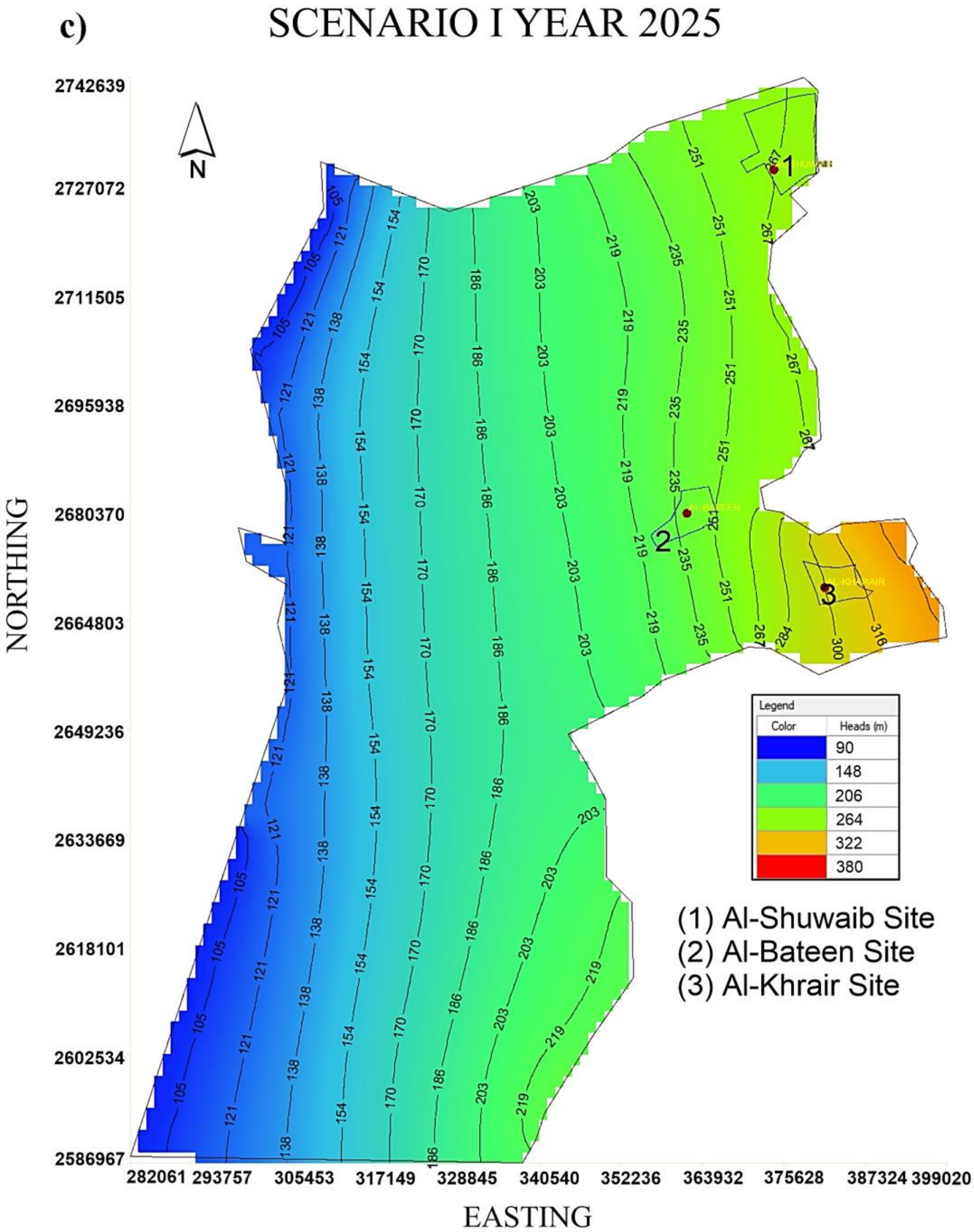


Figure 47: Scenario I simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

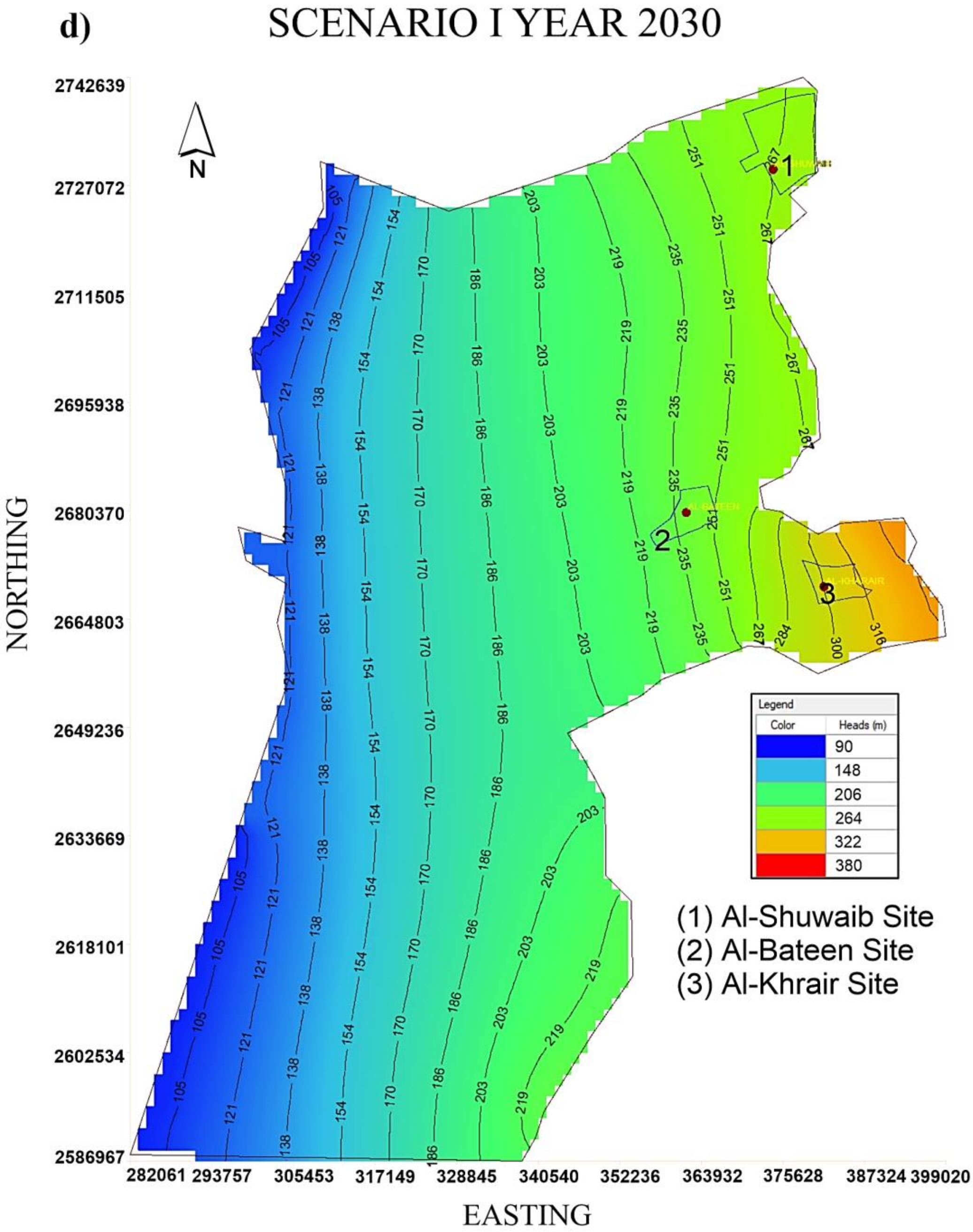


Figure 47: Scenario I simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

6.1.2 Scenario II (Recharge Rate 2,000 m^3/day)

In this scenario, the model was simulated with water recharge rate of 2,000 m^3/day from year 2013 until 2030 through an injection well located at each selected site. This recharge rate is 2 times the recharge rate simulated previously in the study area (Hutchinson, 1998). The simulated hydraulic heads had increased with a noticeable rise in Al-Bateen site started to take place from the year 2015 indicating that this site is more sensitive to water recharges. The hydraulic head at Al-Bateen site increased to 245.7 m in 2030 compared to 245 m in 2015 and at Al-Shuwaib the hydraulic head is 270.8 m in 2030 compared to 269.11 m in 2015 while at Al-Khrair site the hydraulic head is 305.1 m 2030 compared to 303 m in 2015. The simulated hydraulic heads for 2015, 2020, 2025, and 2030 are presented in Figure 48.

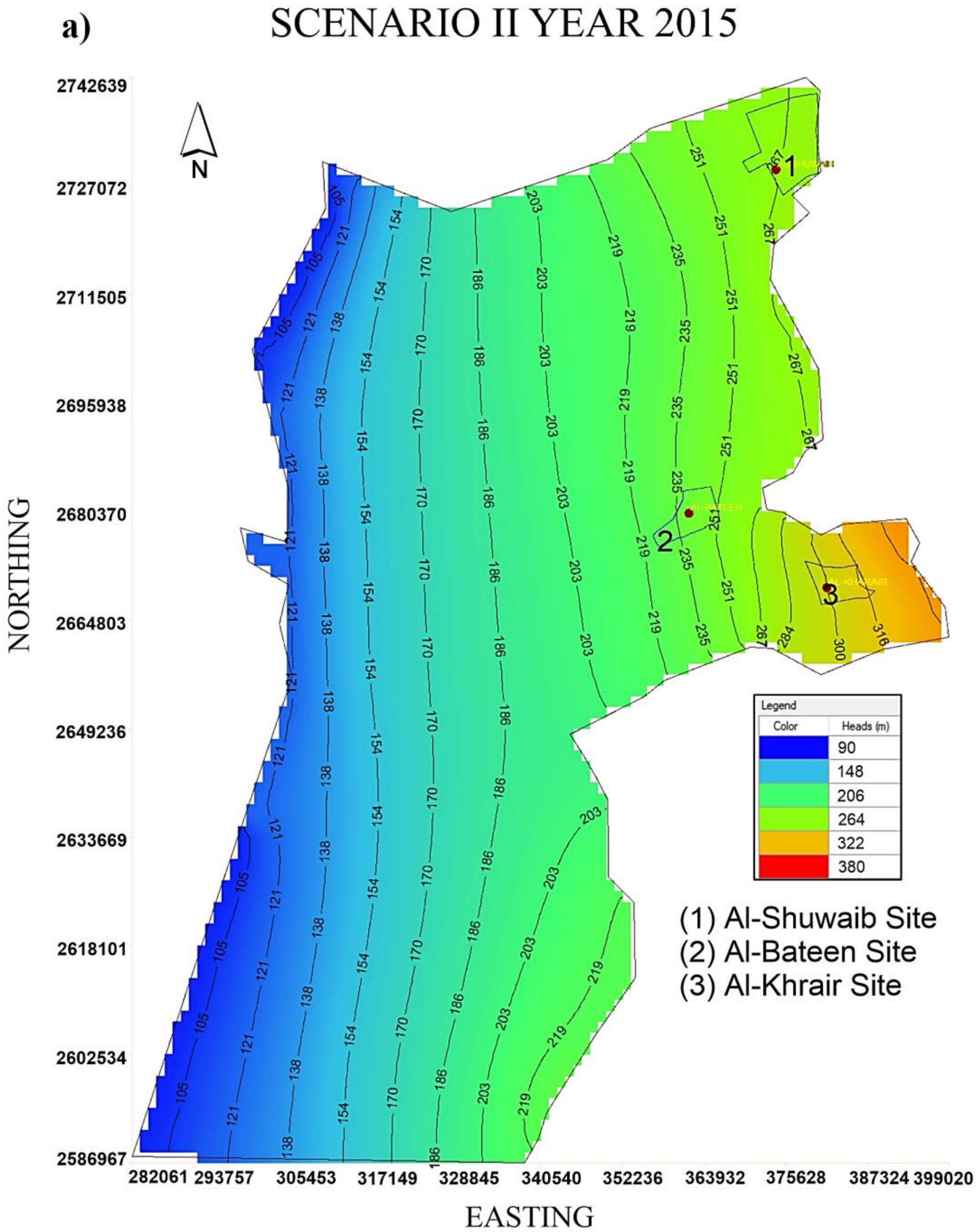


Figure 48: Scenario II simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030

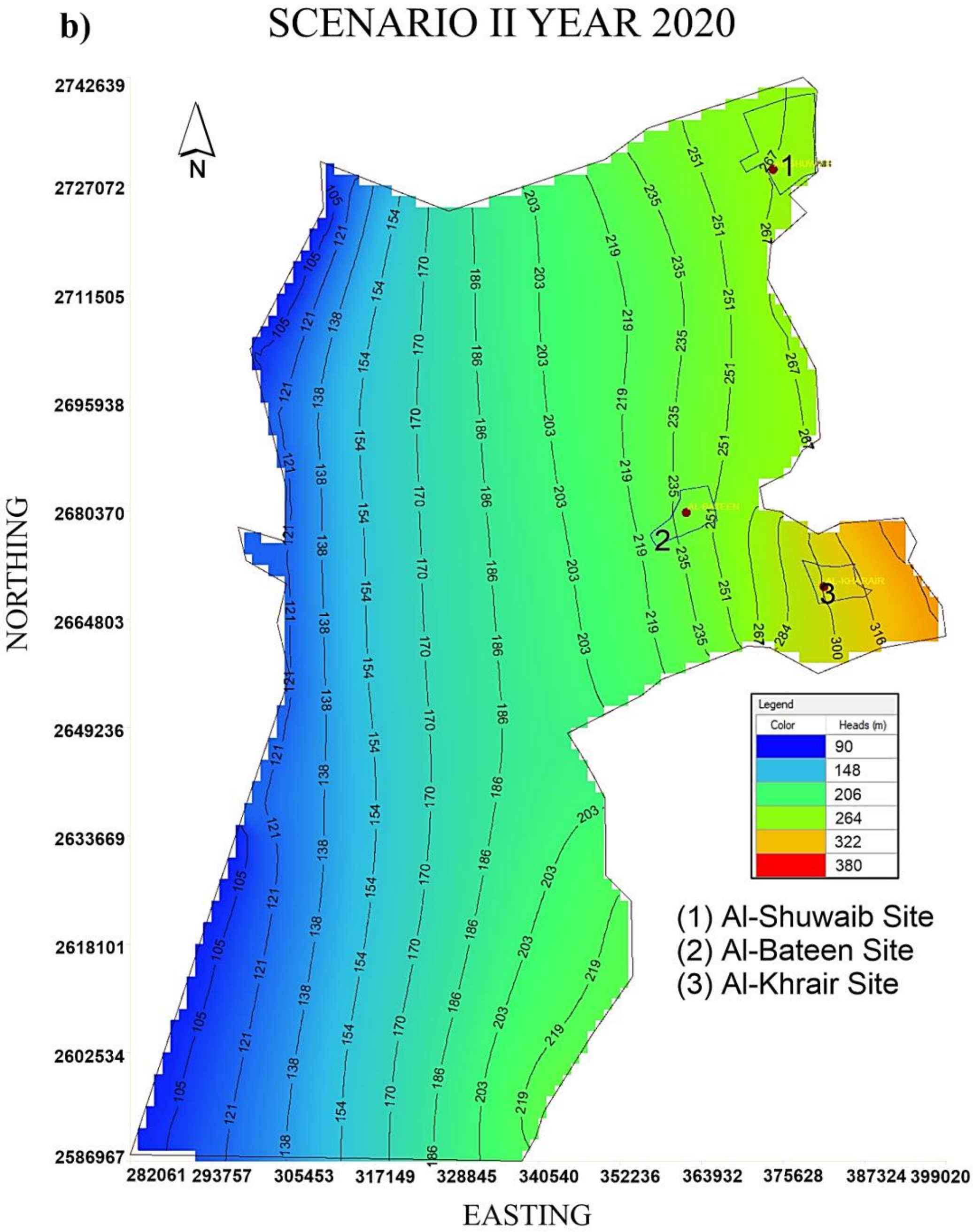


Figure 48: Scenario II simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

c) SCENARIO II YEAR 2025

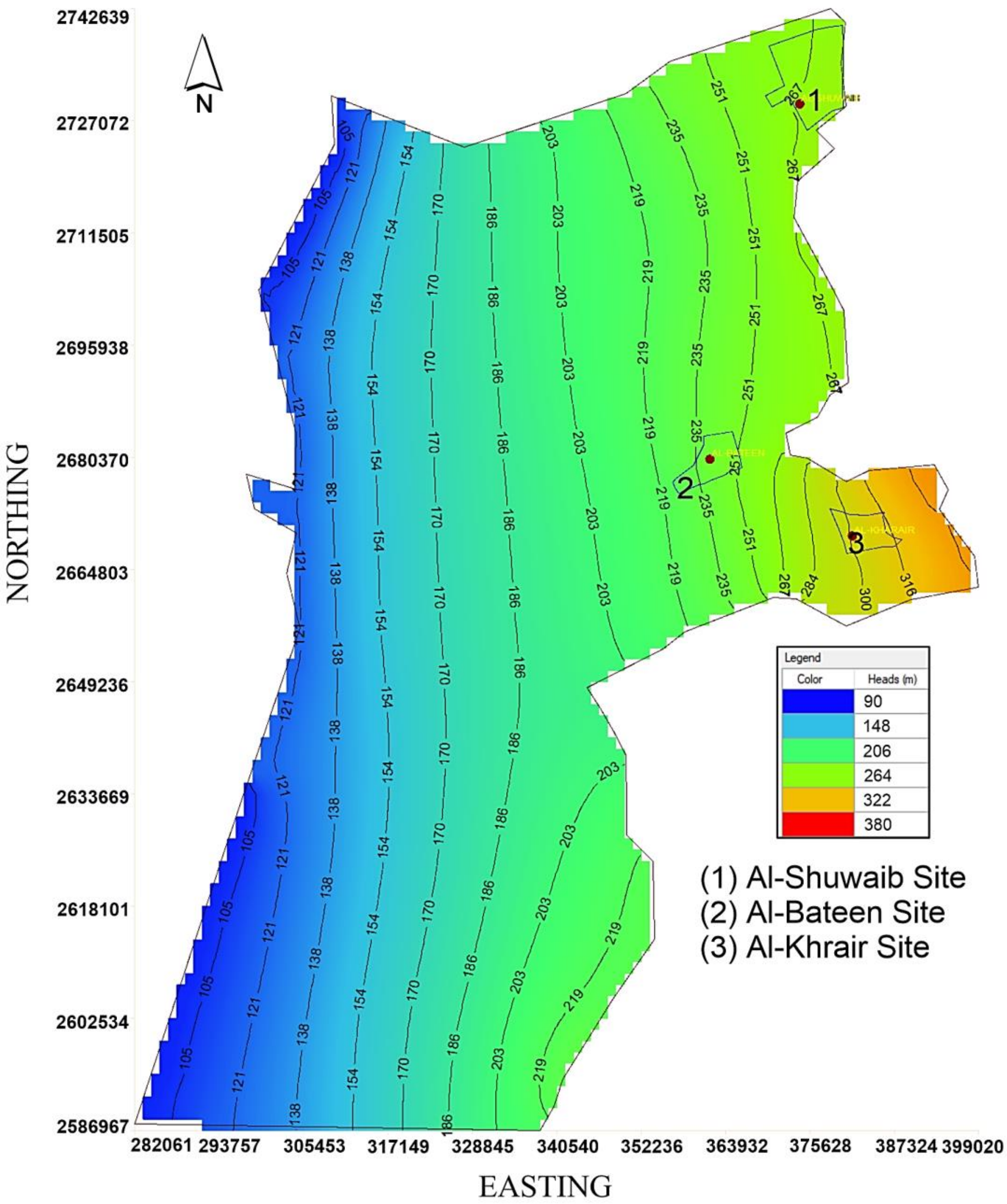


Figure 48: Scenario II simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

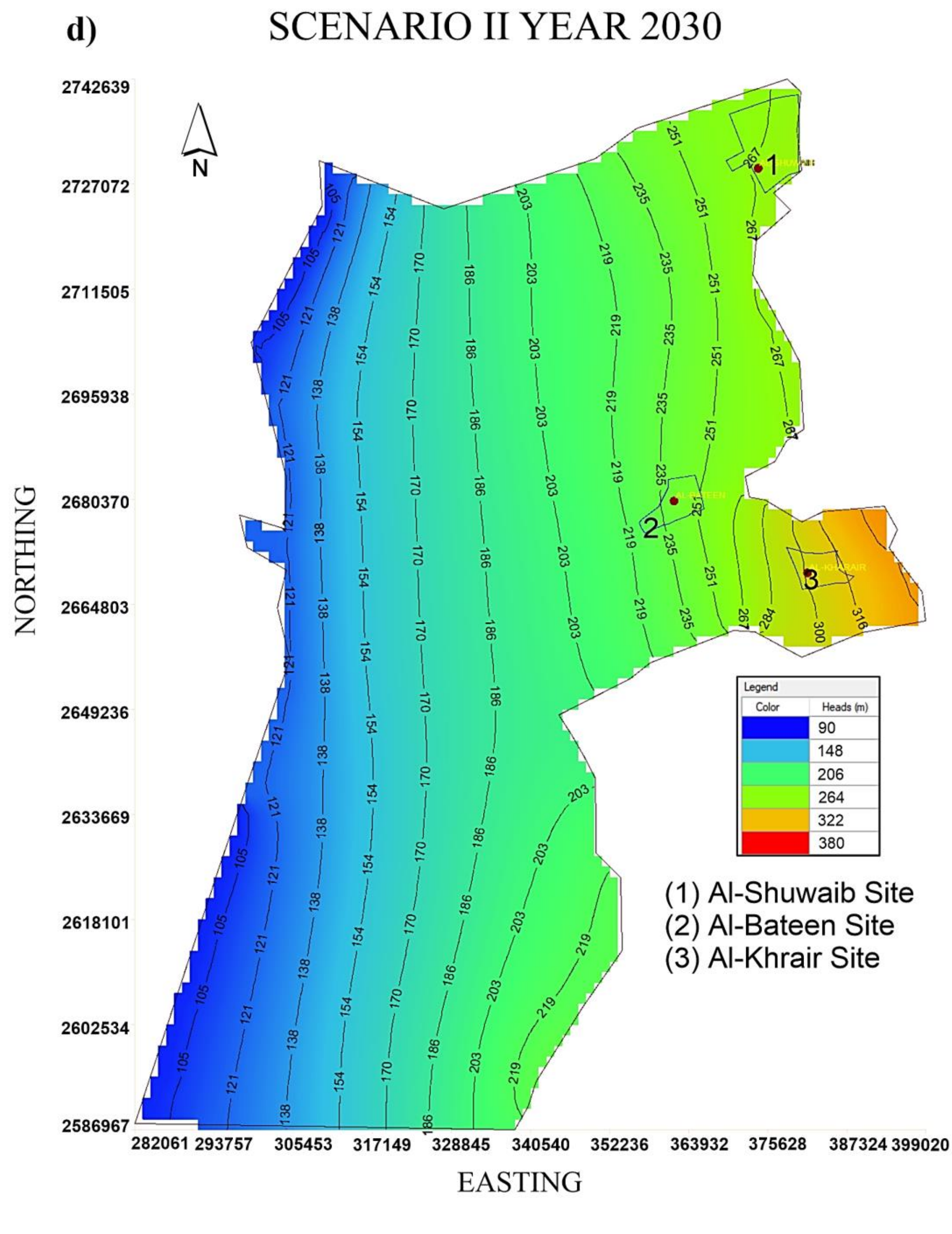


Figure 48: Scenario II simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

6.1.3 Scenario III (Recharge Rate 4,000 m^3/day)

In this scenario, the model was simulated with water recharge rate of 4,000 m^3/day from year 2013 until 2030 through an injection well located at each selected site. This recharge rate is near to the recharge rate simulated previously at Nizwa site, Sharjah (Klingbeil, 2012). The simulated hydraulic heads increased at the location of the injection well significantly in Al-Bateen site with excess water head build-up. For Al-Bateen site, the hydraulic head is 251.4 m in 2030 which show an excessive head build-up. In Al-Shuwaib site, the hydraulic head is 275.14 in 2030 compared to 272 m in 2015 while at Al-Khrair site, the hydraulic head is 310.05 m in 2030 compared to 306.3 m in 2013. The simulated hydraulic heads for 2015, 2020, 2025, and 2030 are presented in Figure 49.

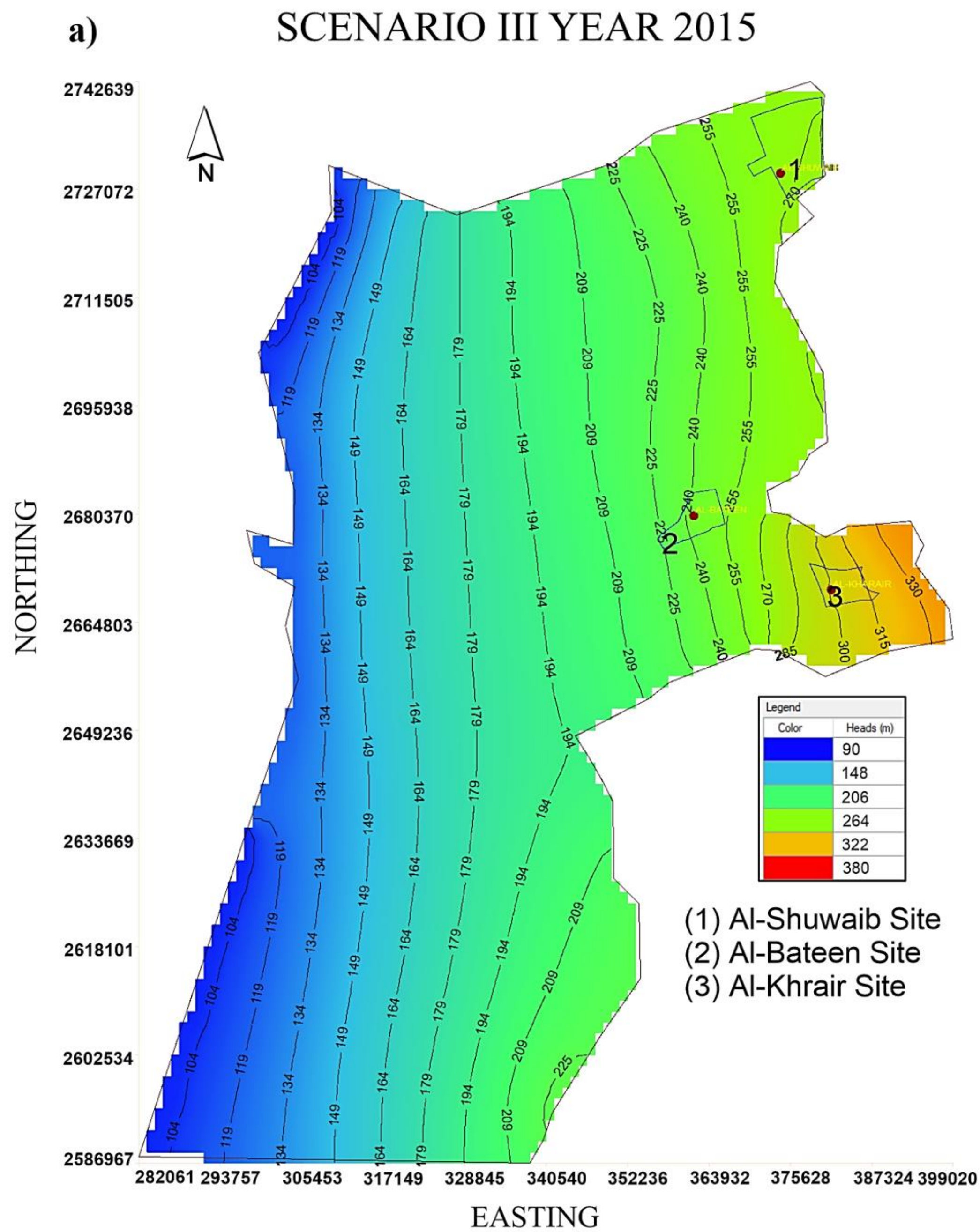


Figure 49: Scenario III simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030

b) SCENARIO III YEAR 2020

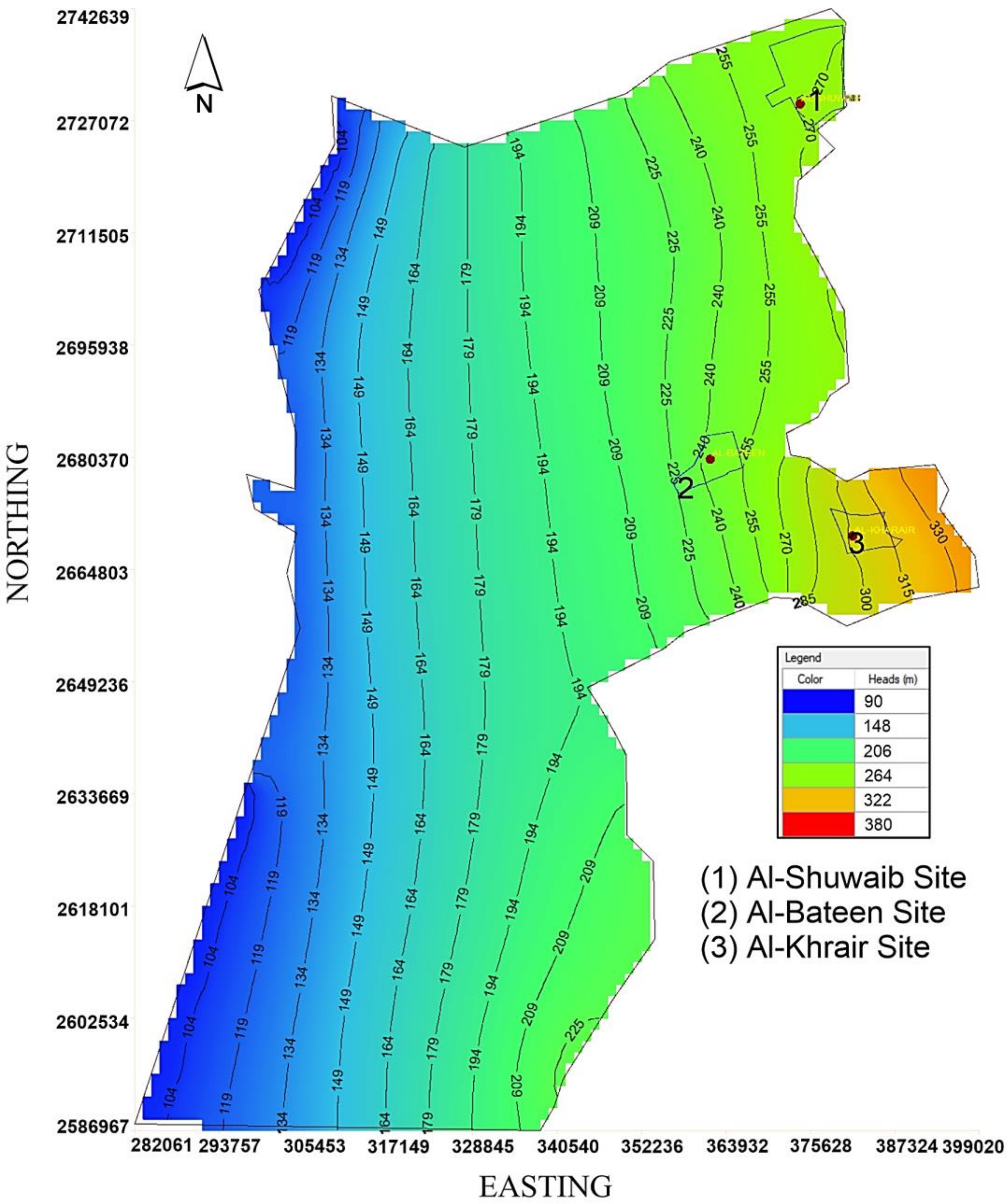


Figure 49: Scenario III simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

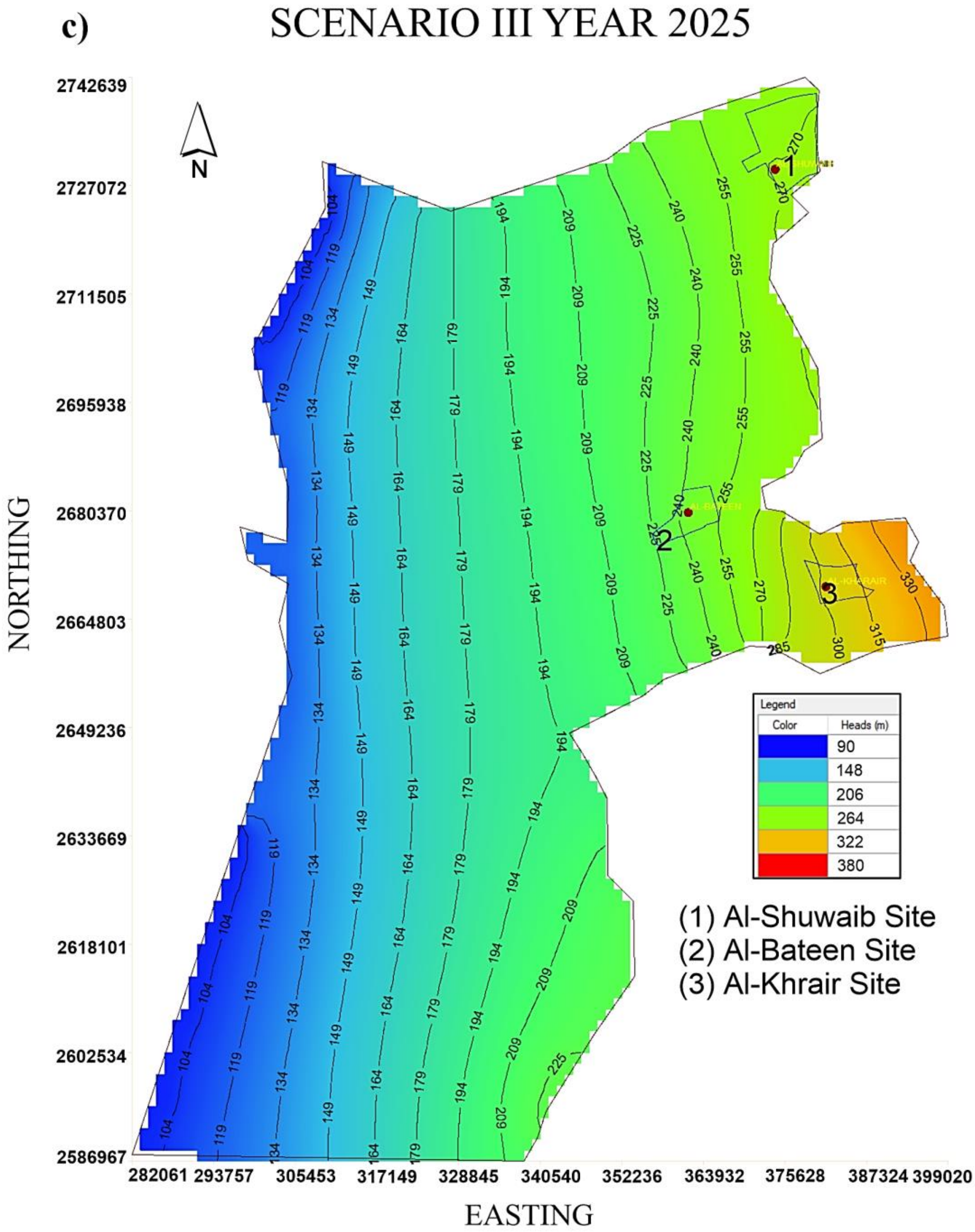


Figure 49: Scenario III simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

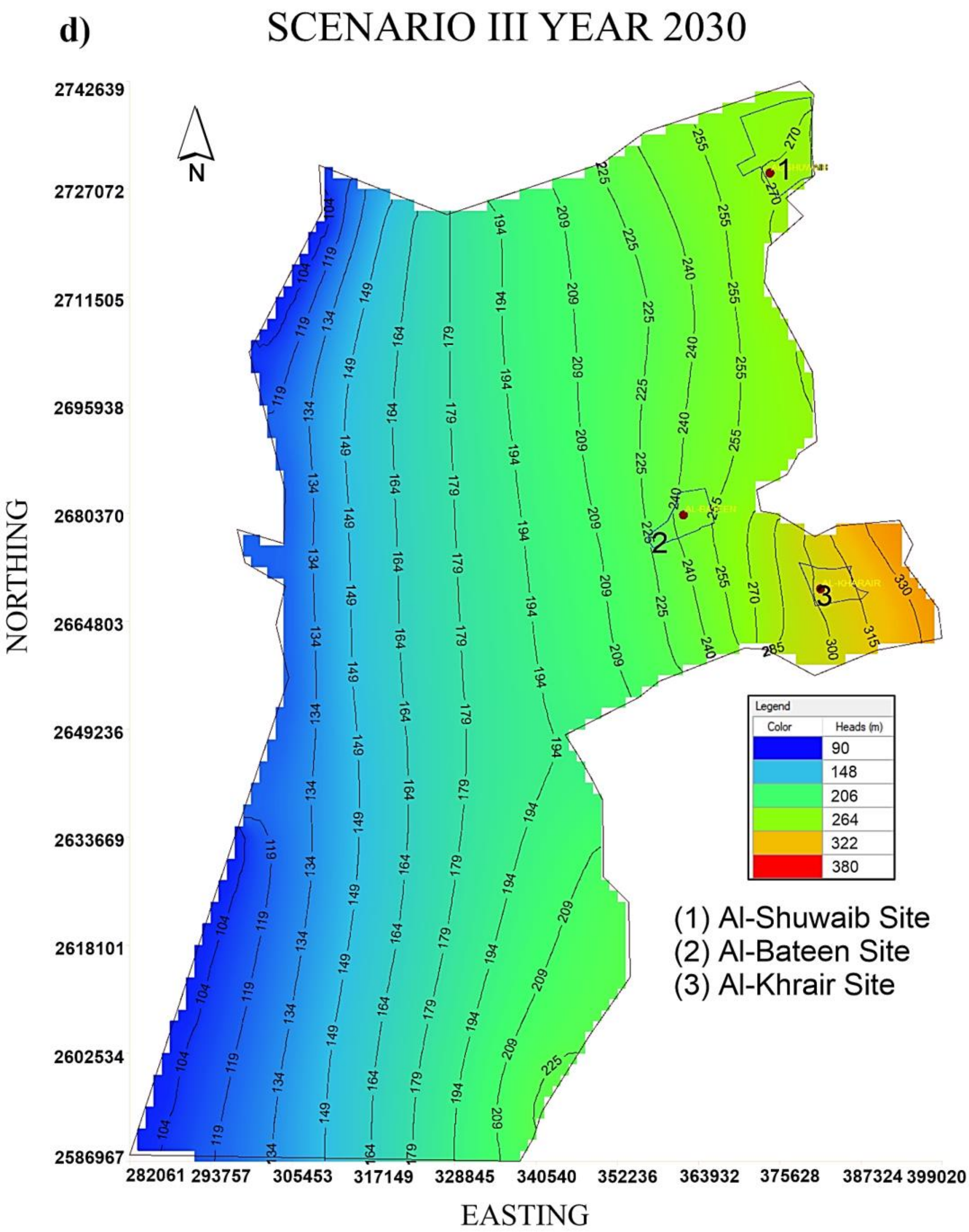


Figure 49: Scenario III simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

6.1.4 Scenario IV (Recharge Rate 8,000 m^3/day)

In this scenario, the model was simulated with water recharge rate of 8,000 m^3/day from year 2013 until 2030 through an injection well located at each selected site. This recharge rate is almost similar to the excess treated wastewater daily discharged to the environment in Al-Ain region (Dawoud, 2017), 8 times greater than the recharge rate simulated previously in the study area (Hutchinson, 1998) and 2,000 m^3 more than the recharge rate simulated in Liwa, Abu Dhabi, UAE. The simulated hydraulic heads for 2015, 2020, 2025, and 2030 increased locally at the location of the injection well with an excessive hydraulic head rise in Al-Bateen site indicating that this site is more sensitive to water recharges. For Al-Shuwaib and Al-Khrair sites, the hydraulic head increased slightly throughout the year until 2030 and a reverse cone of depression were developed. The simulated hydraulic heads for 2015, 2020, 2025, and 2030 are presented in Figure 50.

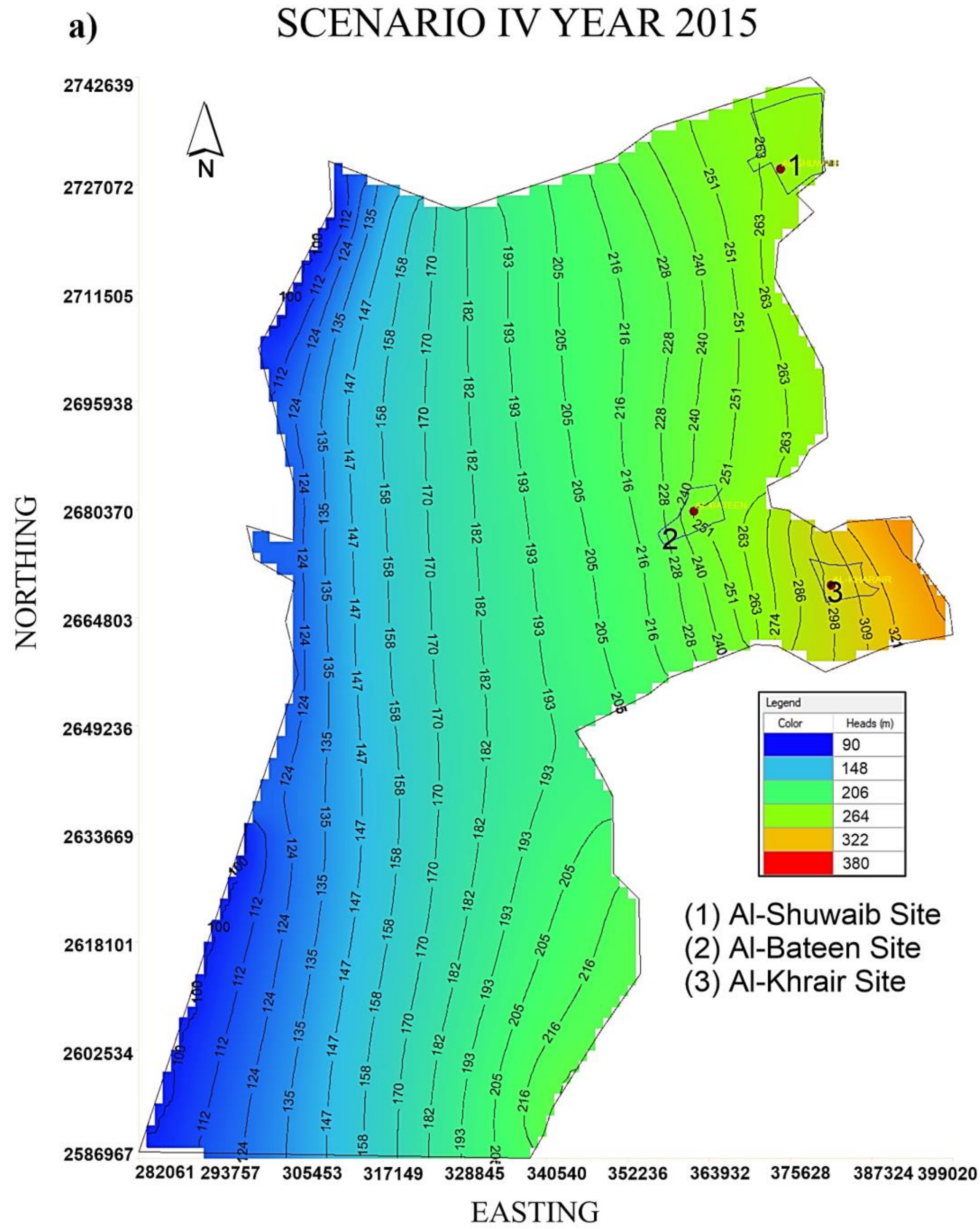


Figure 50: Scenario IV simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030

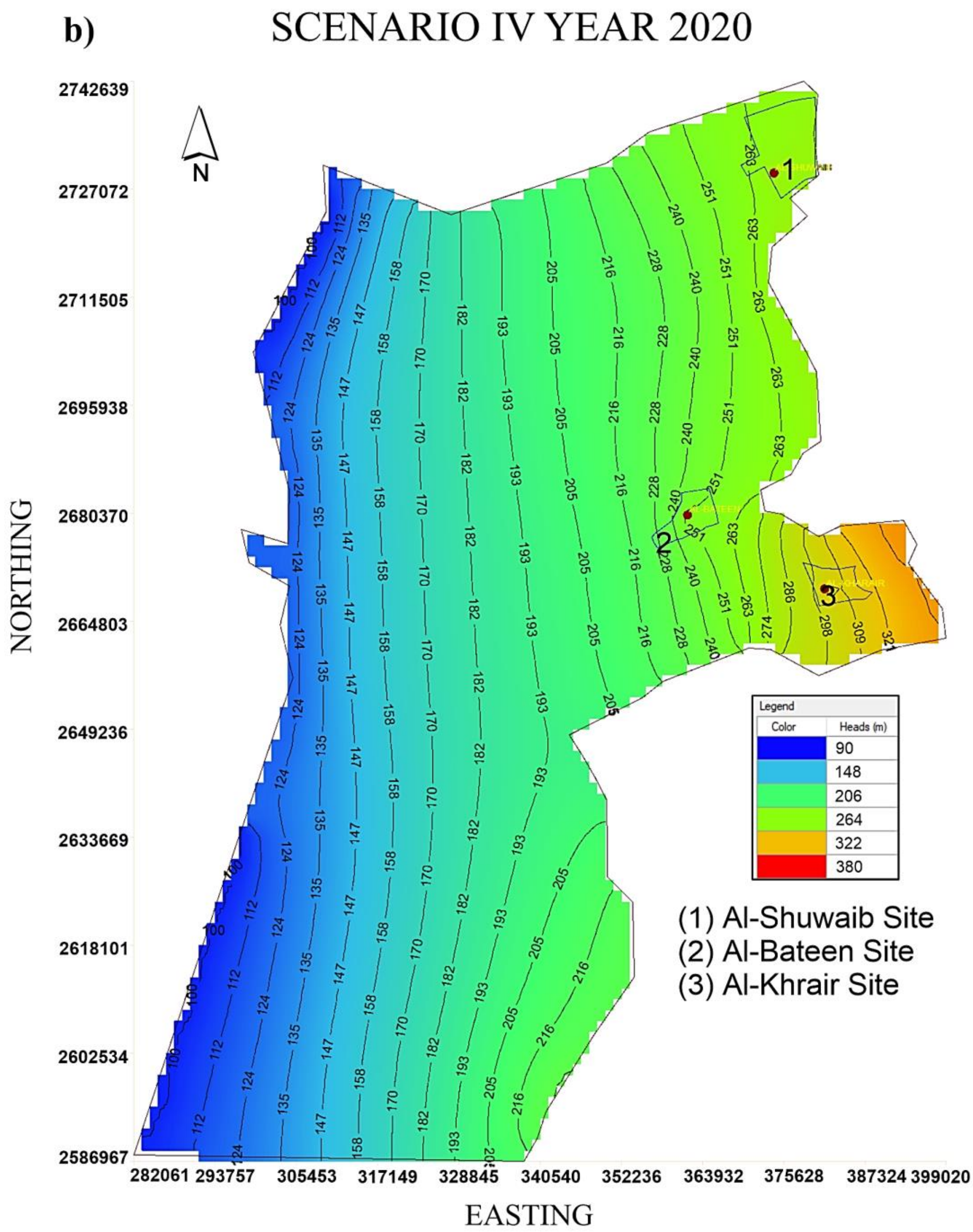


Figure 50: Scenario IV simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

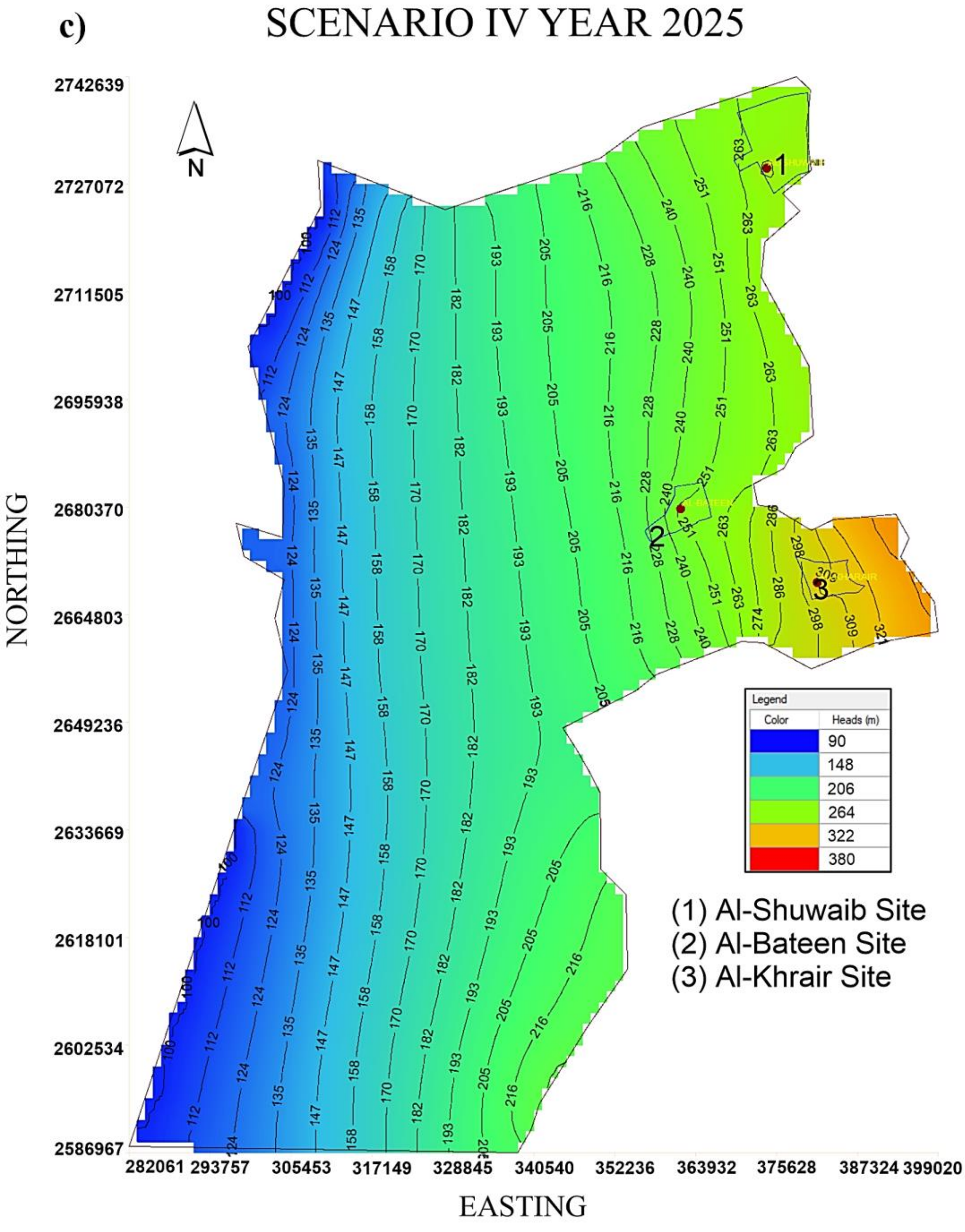


Figure 50: Scenario IV simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

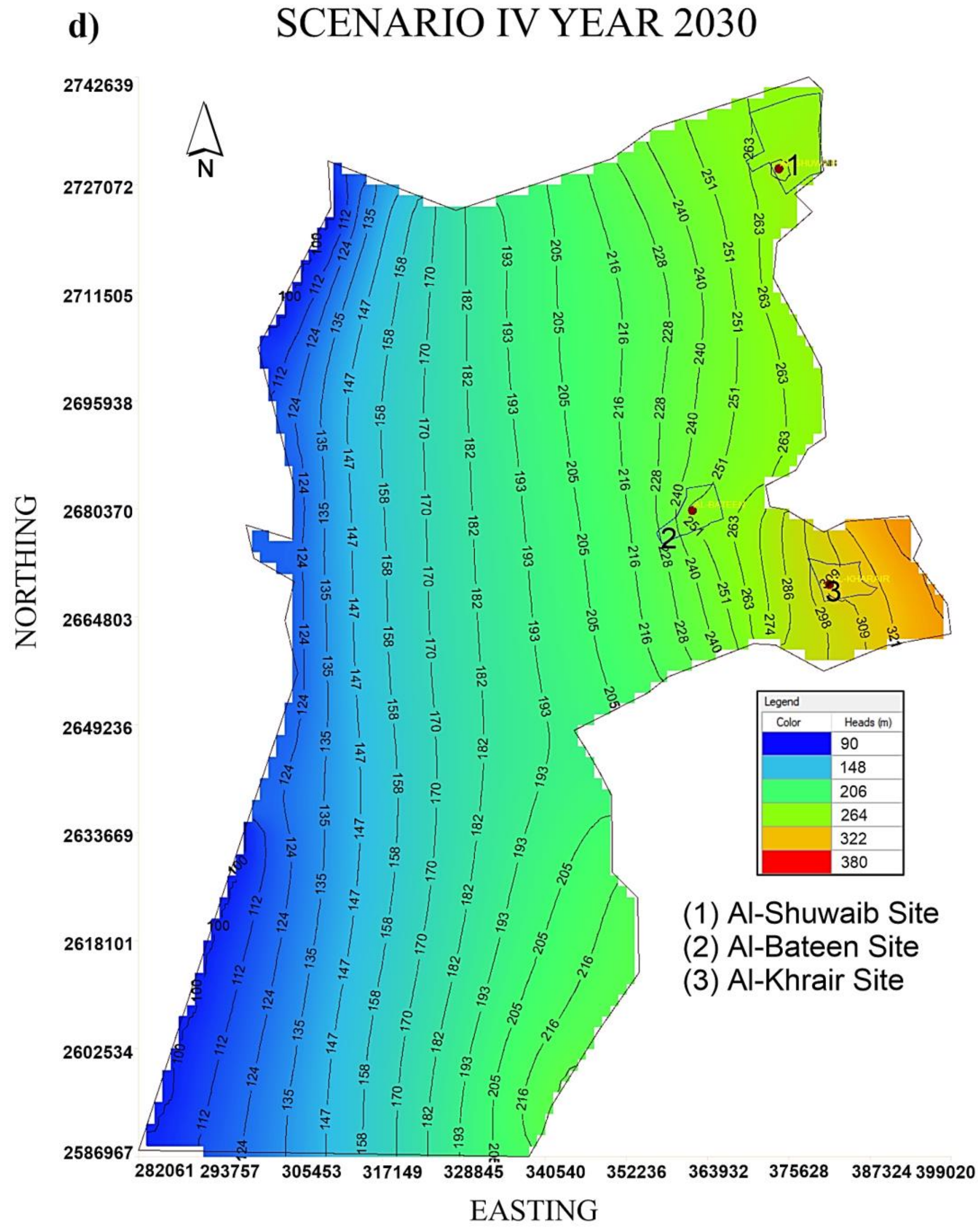


Figure 50: Scenario IV simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 (Continued)

6.1.5 Comparison between Recharge Scenario and the Basic Run

A contour maps for each scenario and the basic run (no water injection in year 2013) were created to show the changes in the groundwater flow behavior and to compare the effect of each water recharge rate on the selected site. For all the maps, the contour interval is 5 m (hydraulic head) for better comparisons.

The hydraulic head of 2013 contour line (black solid line) represents the head when the water recharge from injection wells is zero while the hydraulic head at the years of 2015, 2020, 2025, and 2030 is represented as a red solid line while the thick red line shown in Al-Shuwaib site maps is the project's boundary. The comparison between the basic run and recharge scenarios is presented in Figures 51, 52, and 53.

a) SCENARIO I (RECHARGE RATE 1,000 m^3/day)

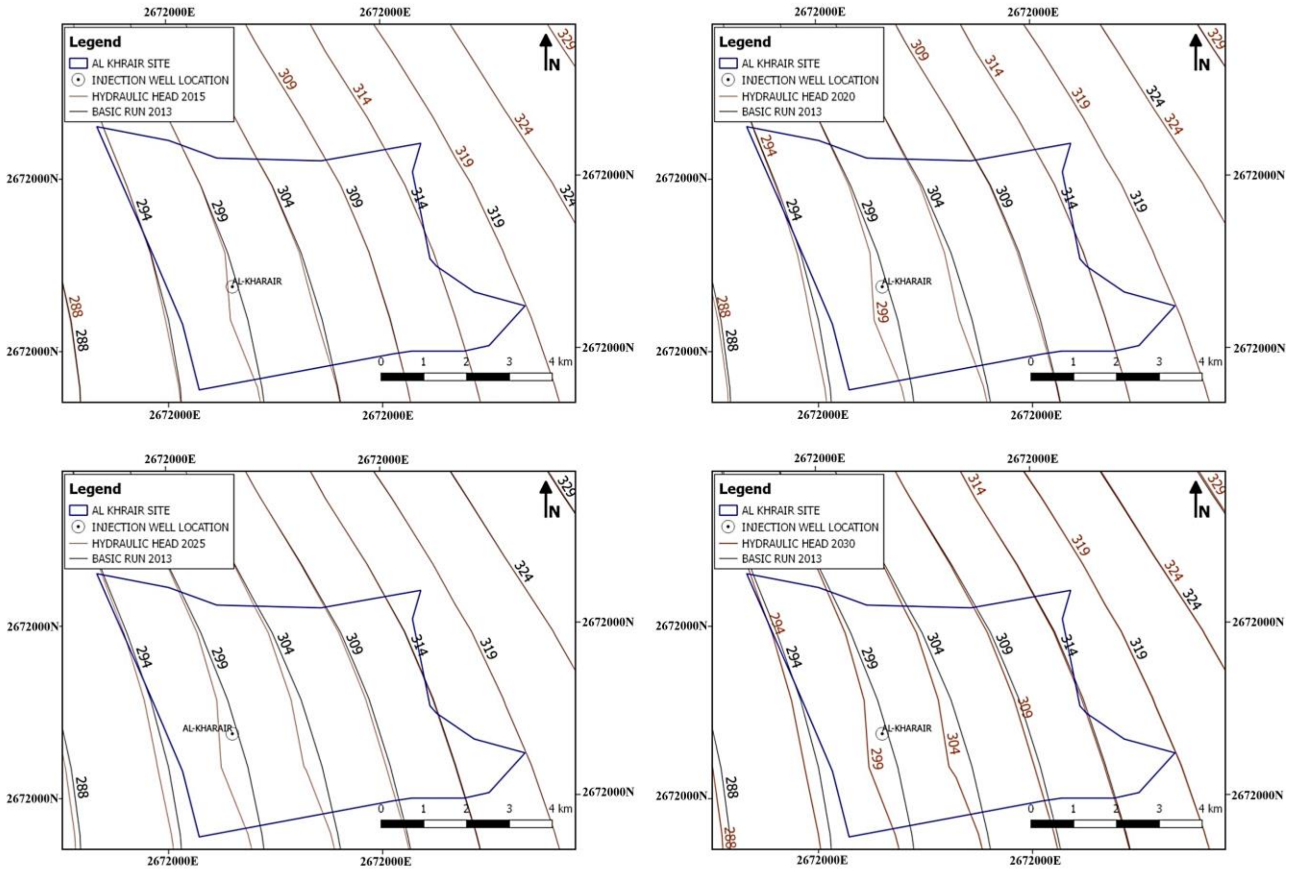


Figure 51: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Khrair Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV

b) SCENARIO II (RECHARGE RATE 2,000 m^3/day)

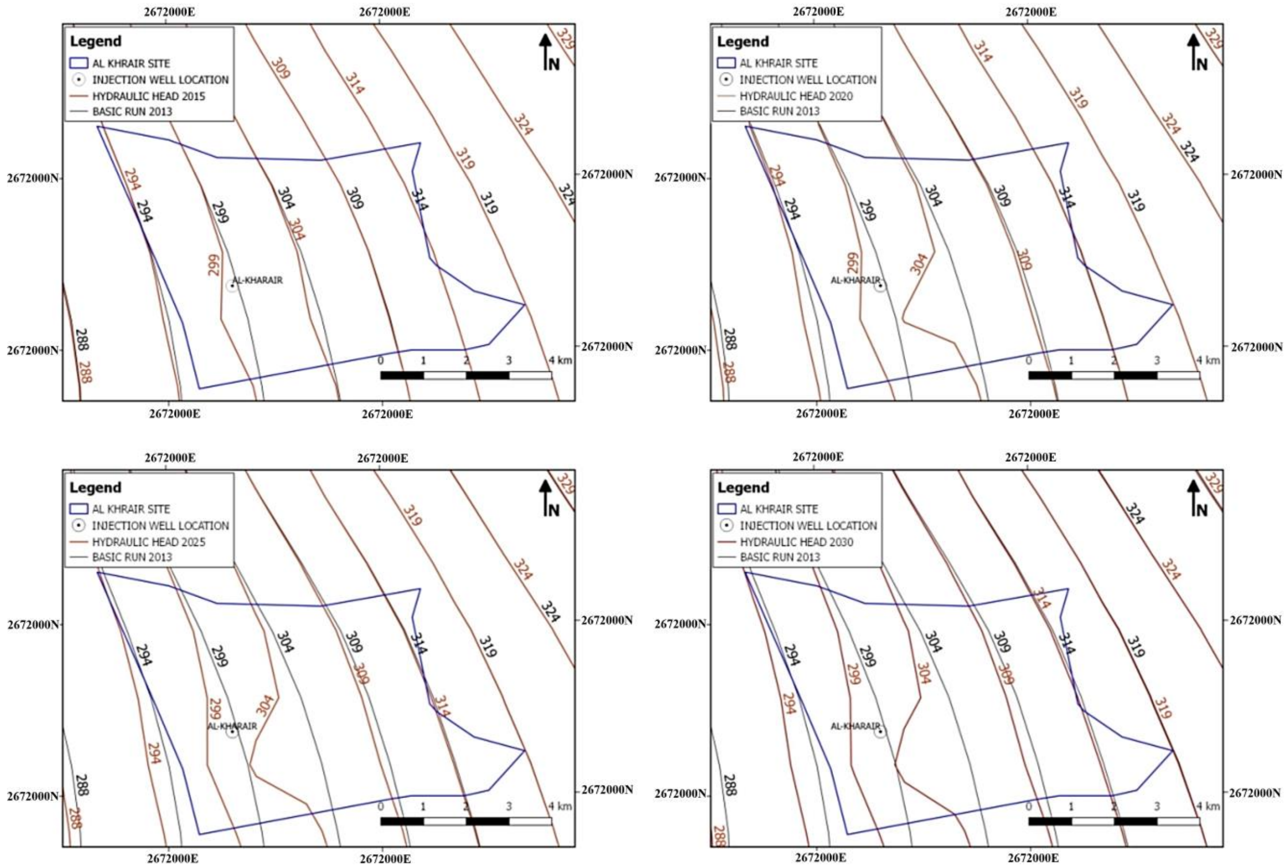


Figure 51: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Khrair Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

c) SCENARIO III (RECHARGE RATE 4,000 m^3/day)

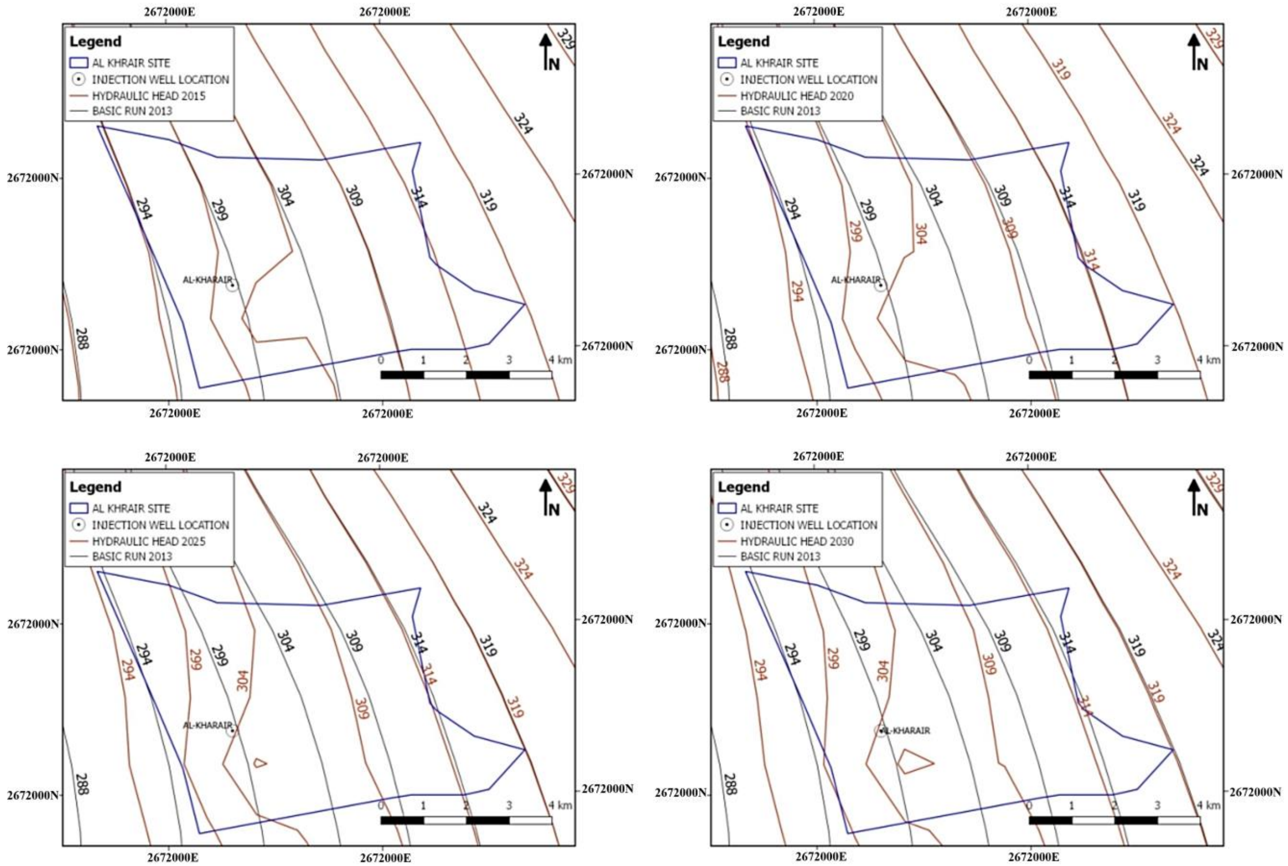


Figure 51: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Khrair Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

d) SCENARIO IV (RECHARGE RATE 8,000 m^3/day)

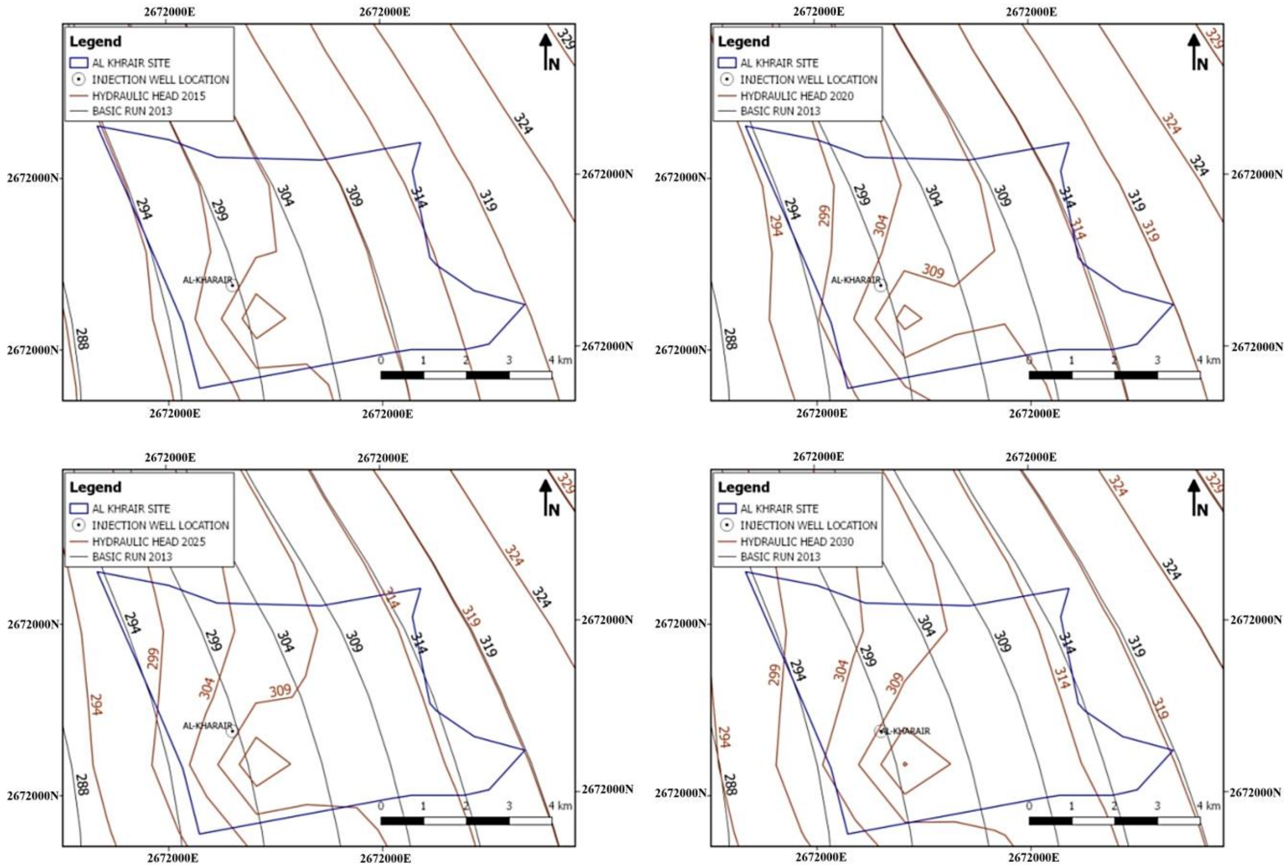


Figure 51: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Khrair Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

a) SCENARIO I (RECHARGE RATE 1,000 m^3/day)

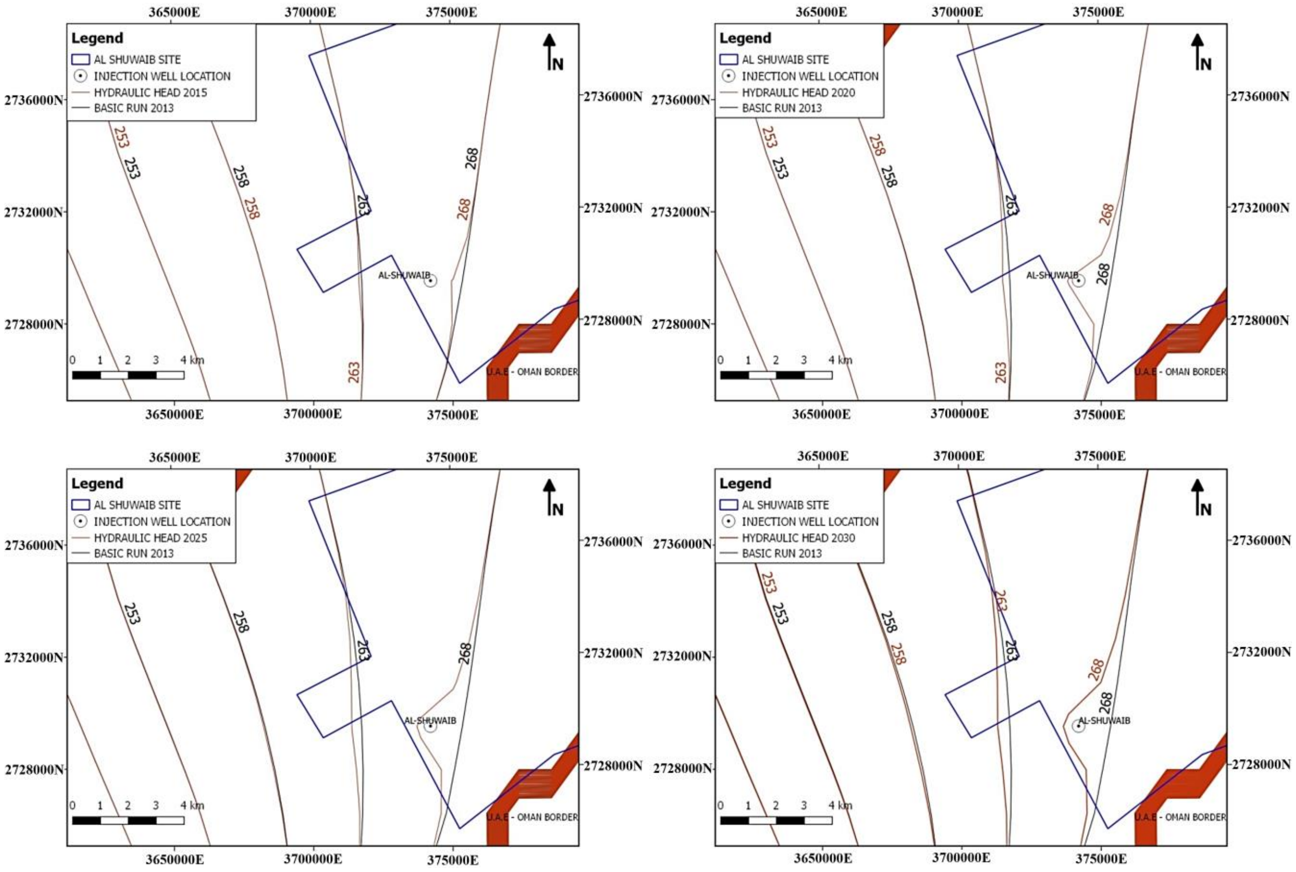


Figure 52: Comparison between recharge scenarios hydraulic heads and the Basic Run (No Water Injection) for Al-Shuwaib Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV

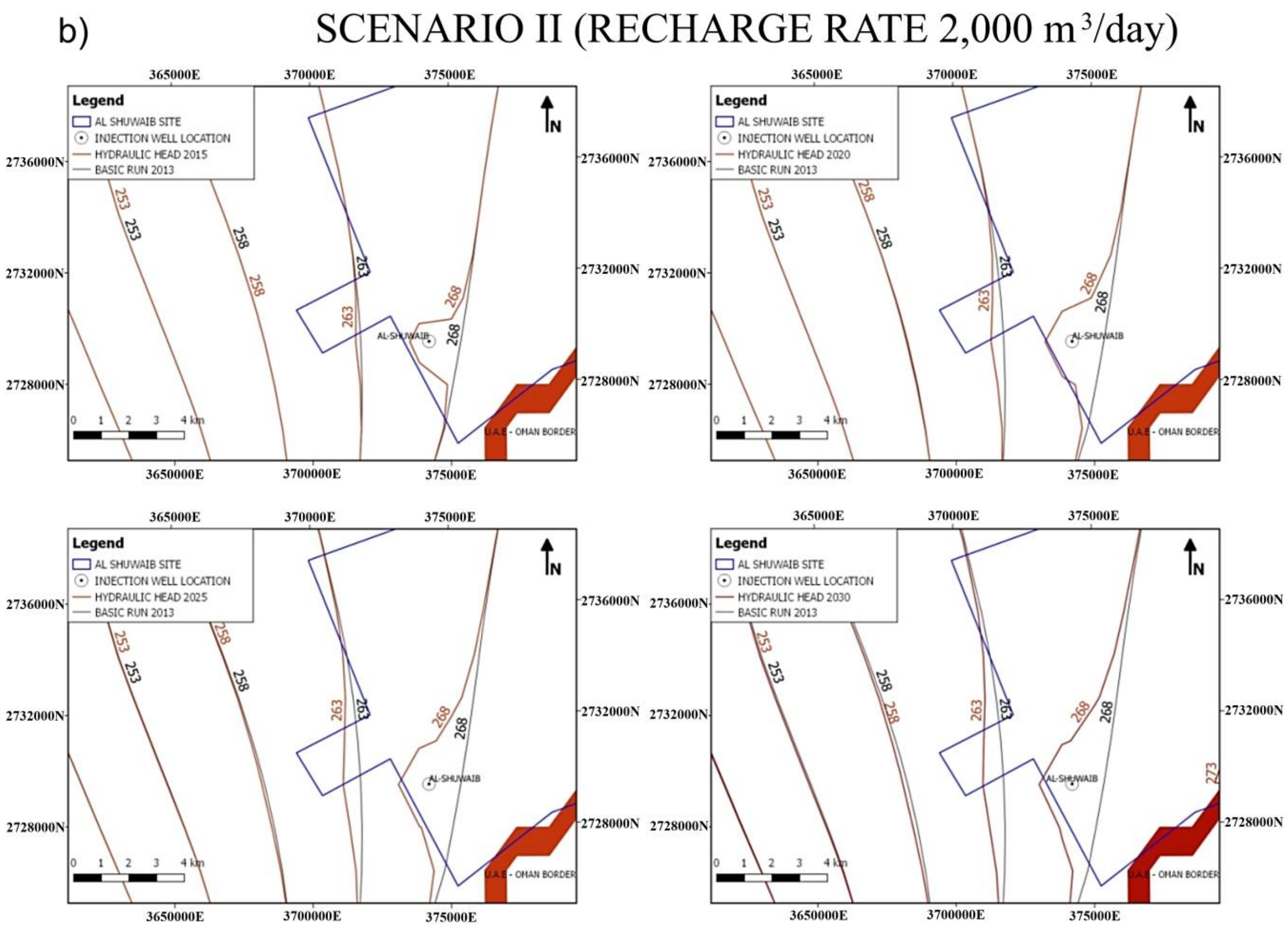


Figure 52: Comparison between recharge scenarios hydraulic heads and the Basic Run (No Water Injection) for Al-Shuwaib Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

c) SCENARIO III (RECHARGE RATE 4,000 m^3/day)

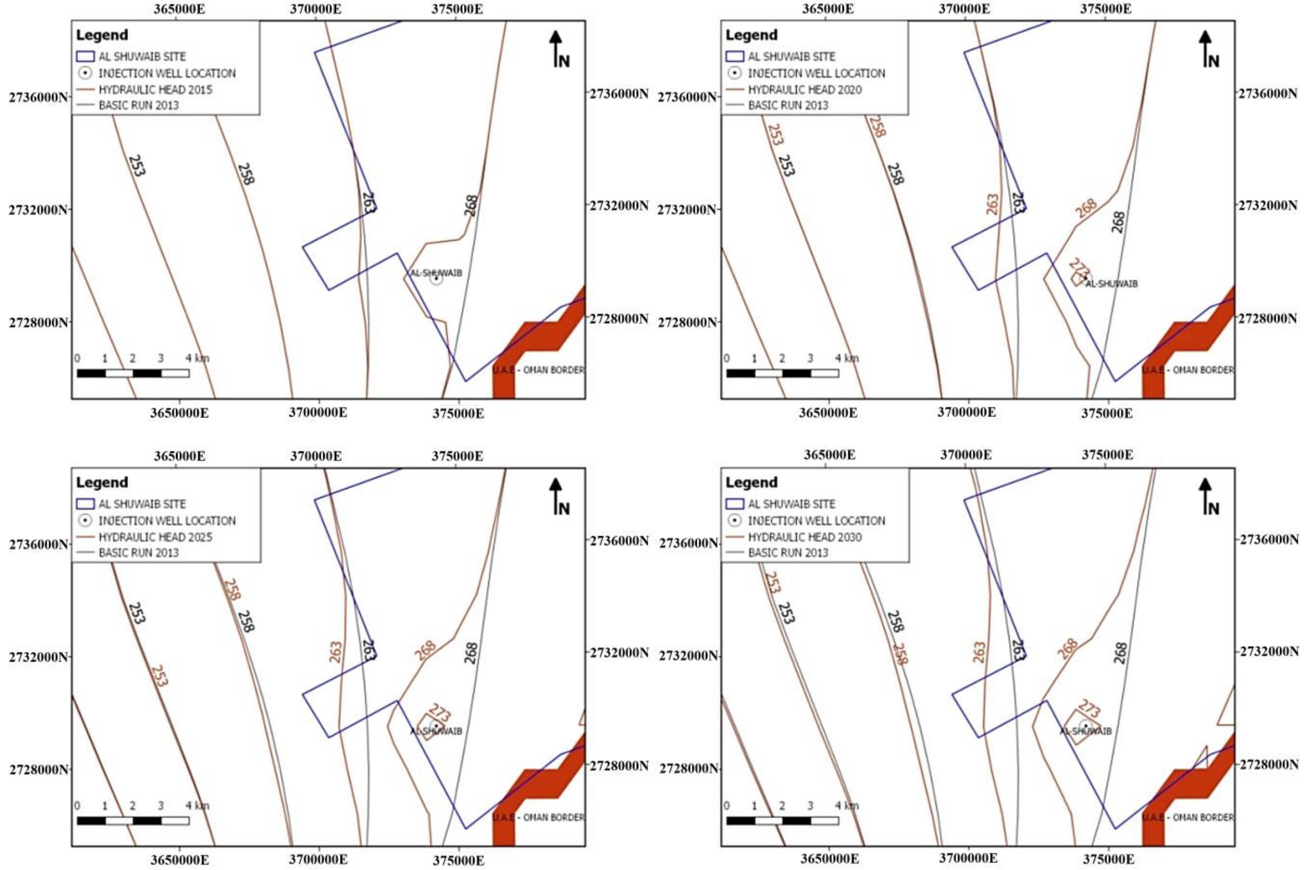


Figure 52: Comparison between recharge scenarios hydraulic heads and the Basic Run (No Water Injection) for Al-Shuwaib Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

d) SCENARIO IV (RECHARGE RATE 8,000 m^3/day)

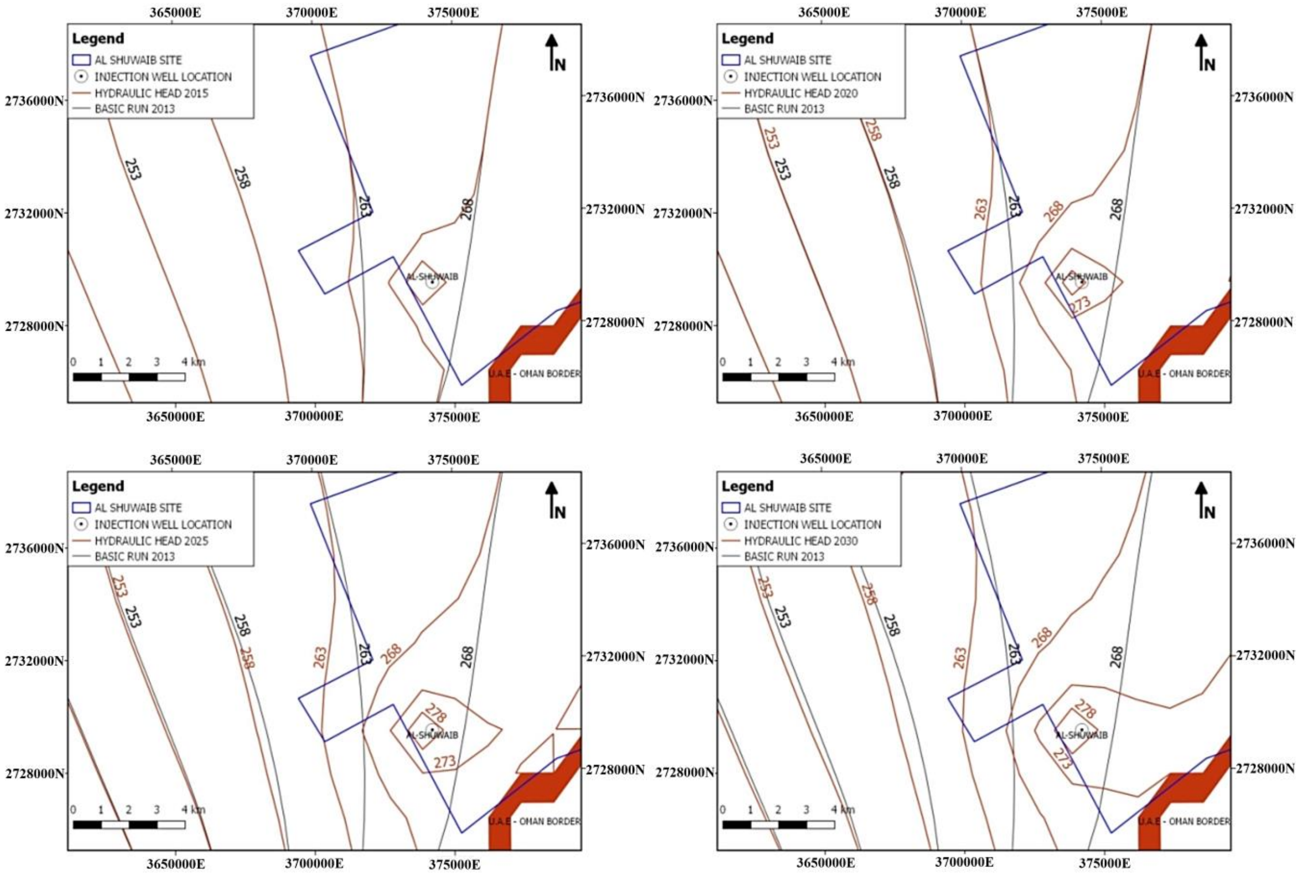


Figure 52: Comparison between recharge scenarios hydraulic heads and the Basic Run (No Water Injection) for Al-Shuwaib Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

a) SCENARIO I (RECHARGE RATE 1,000 m^3/day)

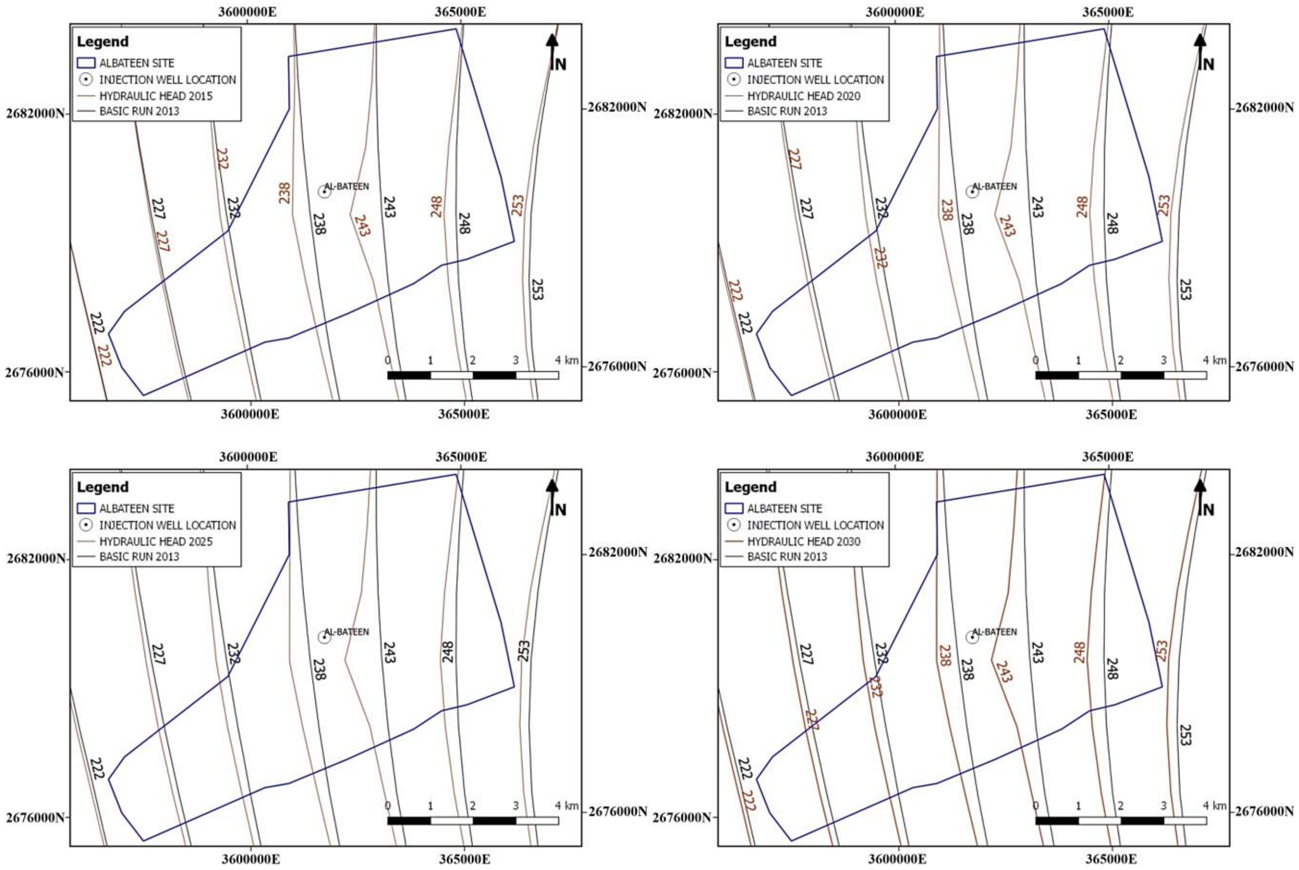


Figure 53: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Bateen Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV

b) SCENARIO II (RECHARGE RATE 2,000 m^3/day)

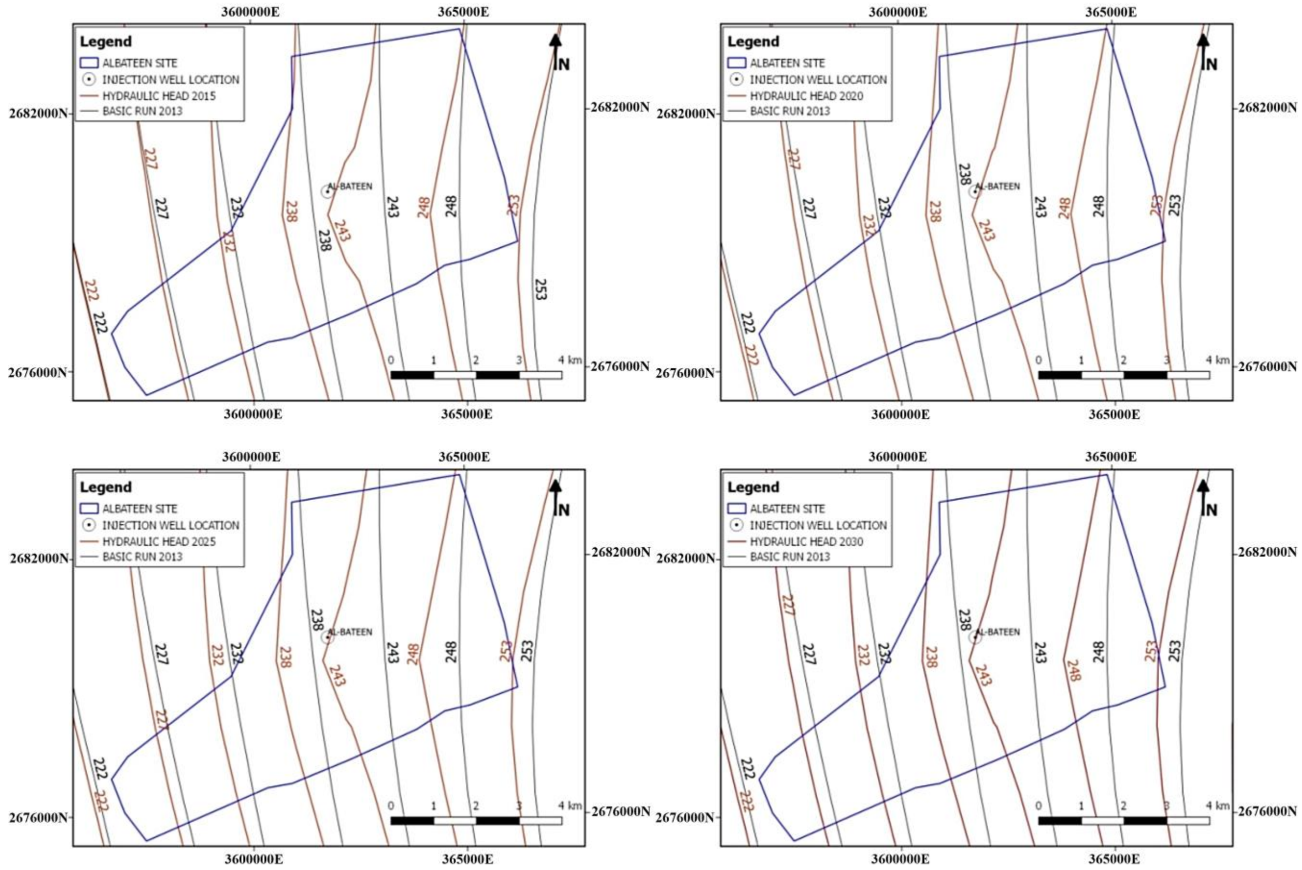


Figure 53: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Bateen Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

c) SCENARIO III (RECHARGE RATE 4,000 m^3/day)

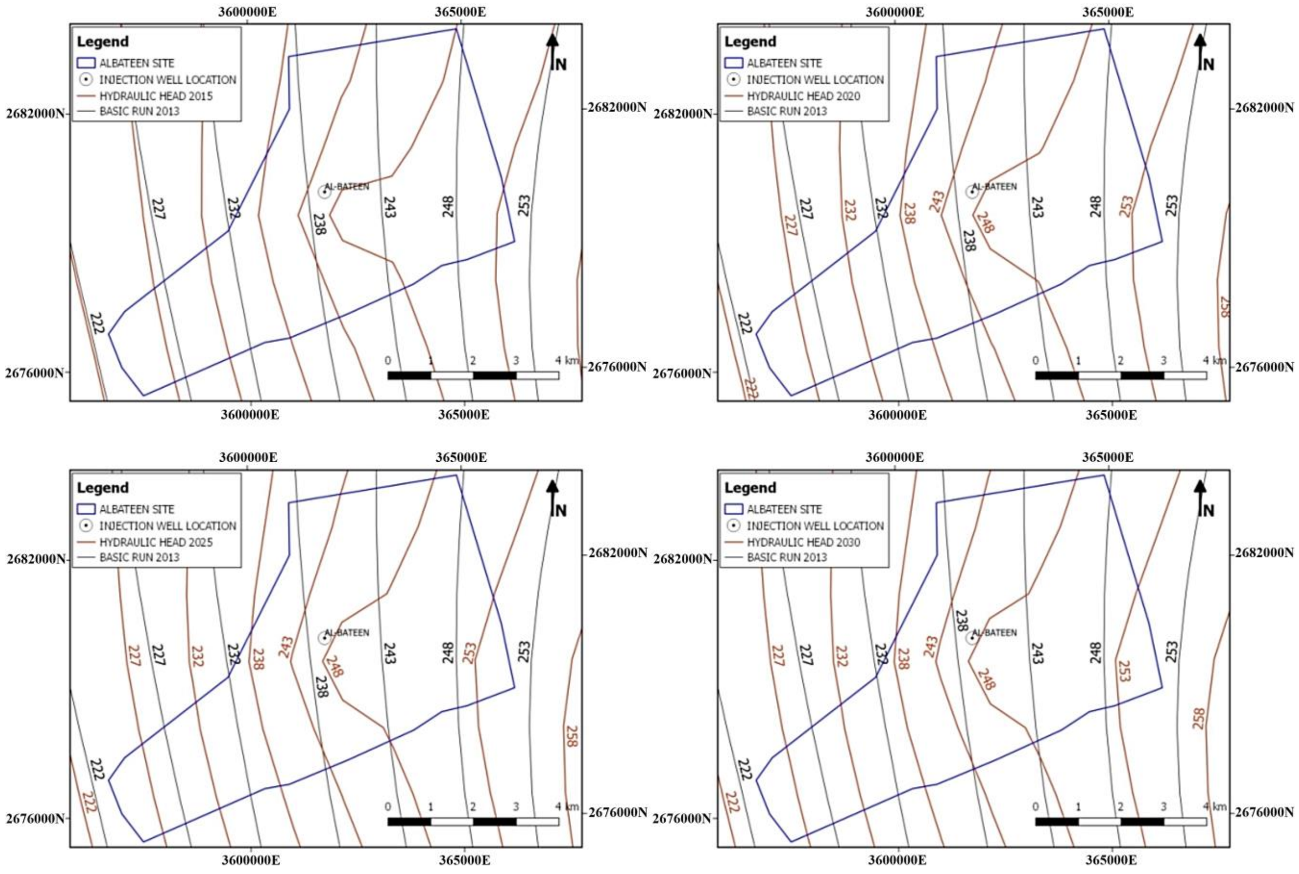


Figure 53: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Bateen Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

d) SCENARIO IV (RECHARGE RATE 8,000 m^3/day)

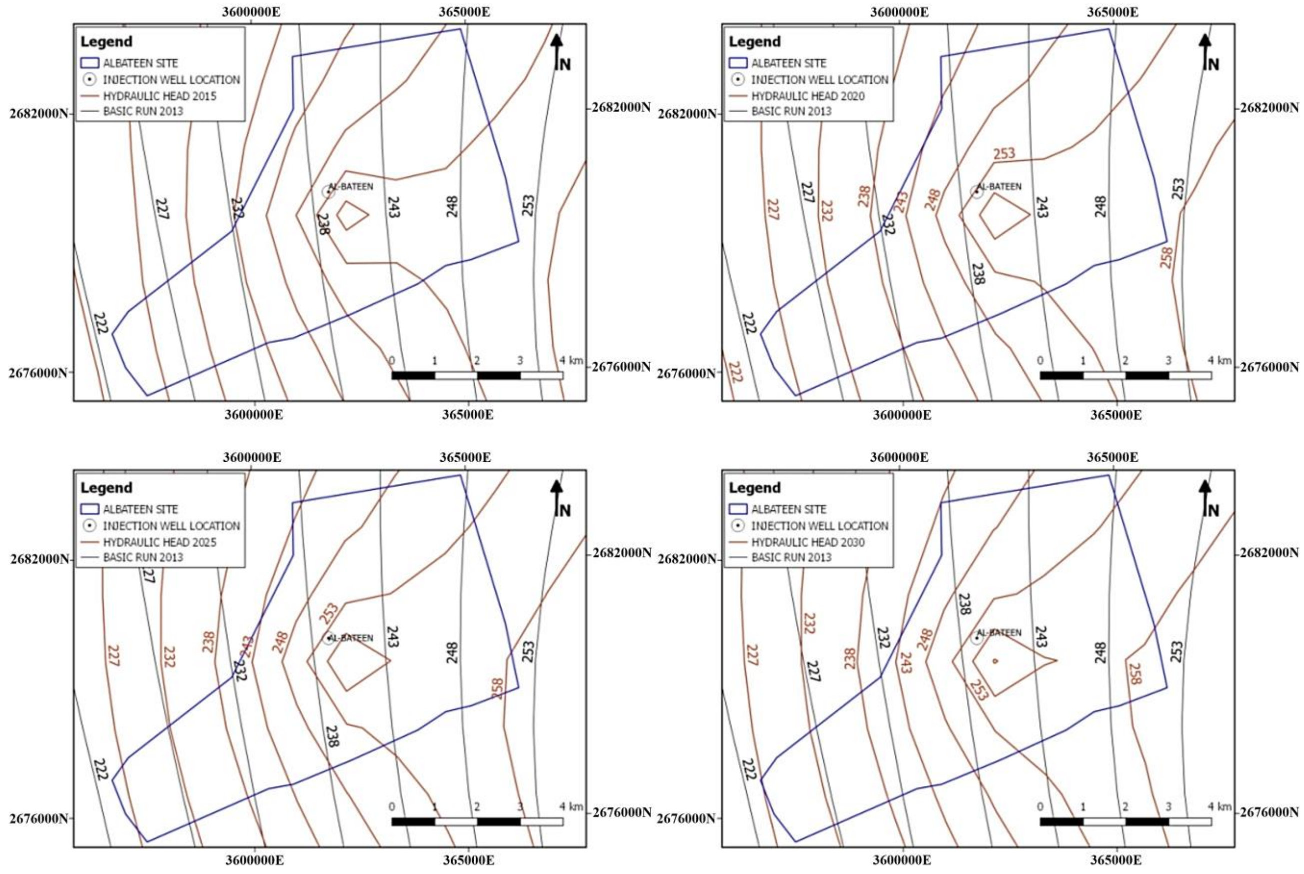


Figure 53: Comparison between recharge scenarios hydraulic head and the Basic Run (No Water Injection) for Al-Bateen Site a) Scenario I, b) Scenario II, c) Scenario III, and d) Scenario IV (Continued)

As a result, the obtained hydraulic heads in each site indicated an expected increase in the water heads at the location of the injection well. Al-Bateen site showed a significant increase in hydraulic heads as the recharge rate increases as compared to Al-Khrair and Al-Shuwaib sites. An excessive head build-up at Al-Bateen site in the third scenario (recharge rate 4,000 m^3/day) started from year 2015 indicating that this site have a limited water recharge estimated around 2,000 m^3/day. For Al-Shuwaib site, the hydraulic head increases to around 283 m in the fourth scenario at year of 2030 which indicates that the maximum water recharge is estimated to be in the range of 8,000 m^3/day as the hydraulic head is approximately 3.5 meters below ground level. Whilst for Al-Khrair site, the hydraulic water heads increases to around 319 m in the fourth scenario at year 2030 showing the good capacity of this site to be recharged without an excessive head build-up as the hydraulic head is around 10 m below ground surface. However, a reverse cone of depression was formed in all the simulated sites and trending towards the west of the study area as presented in Figures 51, 52, and 53. A summary of the obtained hydraulic head at each site of the four scenarios is listed in Table 27.

Table 27: Summary of the obtained hydraulic heads at each site of the four scenarios

Scenario I (Recharge Rate 1,000 m^3/day)			
Year	**Al-Bateen site**	**Al-Khrair site**	**Al-Shuwaib site**
	Elevation (m): 246	Elevation (m): 330	Elevation (m): 286.5
	Water head (m)	Water head (m)	Water head (m)
2015	242.6	301.3	267.57
2020	242.7	301.9	268
2025	242.86	302.2	268.3
2030	242.93	302.4	268.46

Table 27: Summary of the obtained hydraulic heads at each site of the four scenarios (Continued)

Scenario II (Recharge Rate 2,000 m^3/Day)			
Year	**Al-Bateen site**	**Al-Khrair site**	**Al-Shuwaib site**
	Elevation (m): 246	Elevation (m): 330	Elevation (m): 286.5
	Water head (m)	Water head (m)	Water head (m)
2015	245	303	269.11
2020	245.37	304.2	270.09
2025	245.55	304.7	270.5
2030	245.7	305.1	270.8
Scenario III (Recharge Rate 4,000 m^3/Day)			
Year	**Al-Bateen site**	**Al-Khrair site**	**Al-Shuwaib site**
	Elevation (m): 246	Elevation (m): 330	Elevation (m): 286.5
	Water head (m)	Water head (m)	Water head (m)
2015	250	306.3	272.075
2020	250.7	308.44	273.86
2025	251.1	309.37	274.63
2030	251.4	310.05	275.14
Scenario IV (Recharge Rate 8,000 m^3/Day)			
Year	**Al-Bateen site**	**Al-Khrair site**	**Al-Shuwaib site**
	Elevation (m): 246	Elevation (m): 330	Elevation (m): 286.5
	Water head (m)	Water head (m)	Water head (m)
2015	260.3	312.4	277.63
2020	261.67	315.9	280.7
2025	262.57	317.9	282.03
2030	263.33	319.3	282.9

Based on the above results, a further assessment for the most suitable location for an ASR project between Al-Shuwaib and Al-Khrair sites only was implemented due to their ability to be recharged with 8,000 m^3/day. Al-Bateen site was excluded from this assessment due to it is excessive head build-up which limits water injection rate to around 2,000 m^3/day.

6.2 ASR Scenarios for the Selected Sites

The ASR scenarios aim to recharge Al-Shuwaib and Al-Khrair sites with the 23 MCM surplus from desalination plants in Abu Dhabi (Klingbeil, 2012). The 23 MCM is equivalent to around 64,000 m^3/day that will be simulated through multiple injection wells rather than a single well to overcome the excessive head build-up. Furthermore, a recharge values of 64,000 m^3/day, 32,000 m^3/day and 16,000 m^3/day will be simulated to find out the best site for an ASR project.

6.2.1 Injection Wells Distribution

A closed space injection wells with distance around 1,200 m from each other were assigned to each site. The closed space distribution of injection wells are shown in Figure 54.

a)

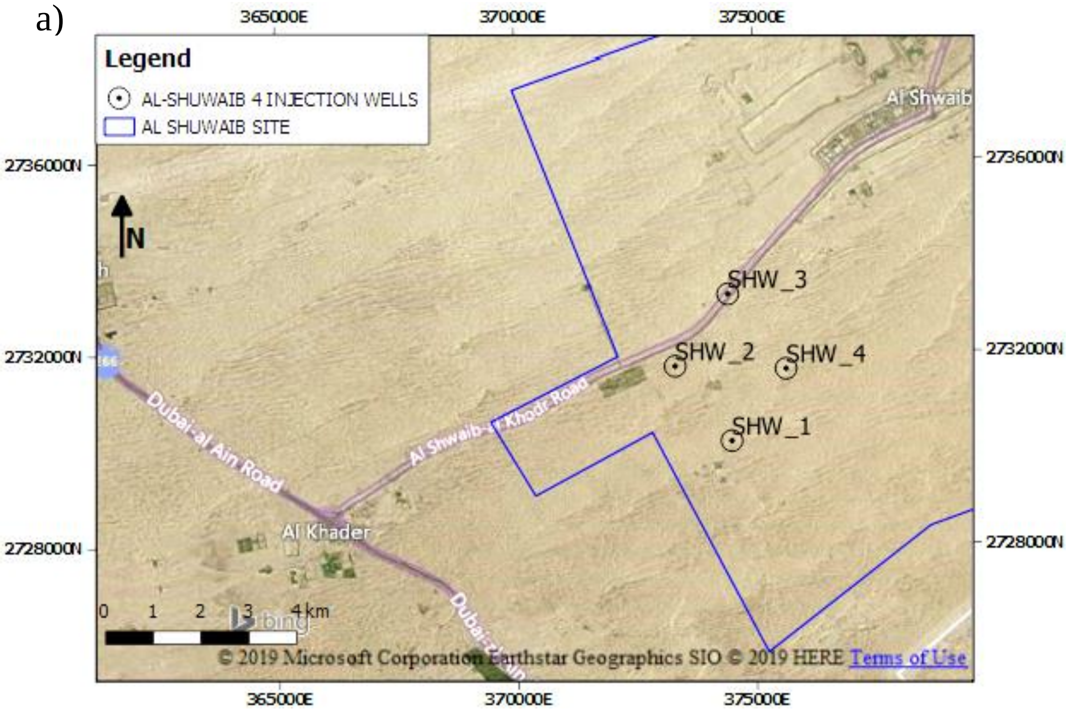
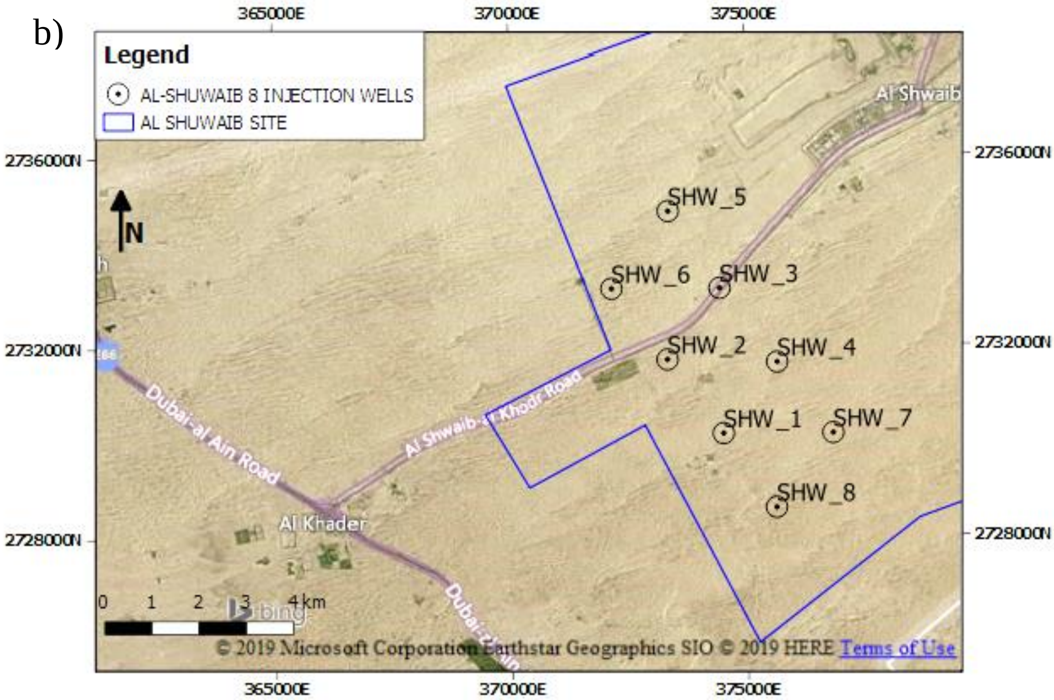


Figure 54: Closed space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells

b)



c)

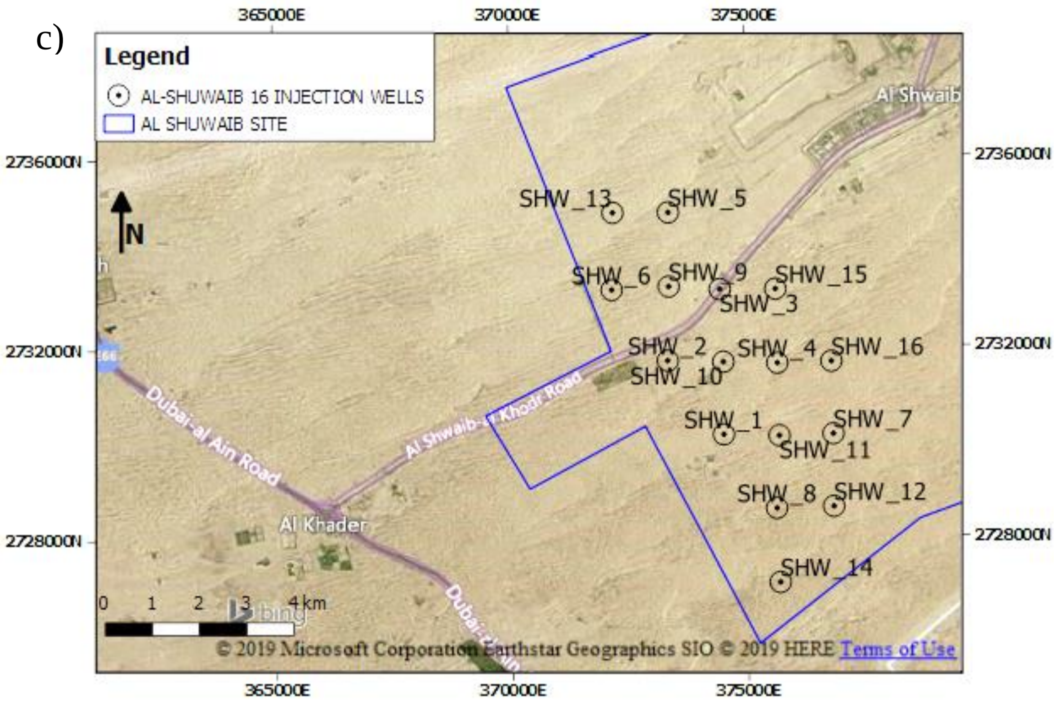
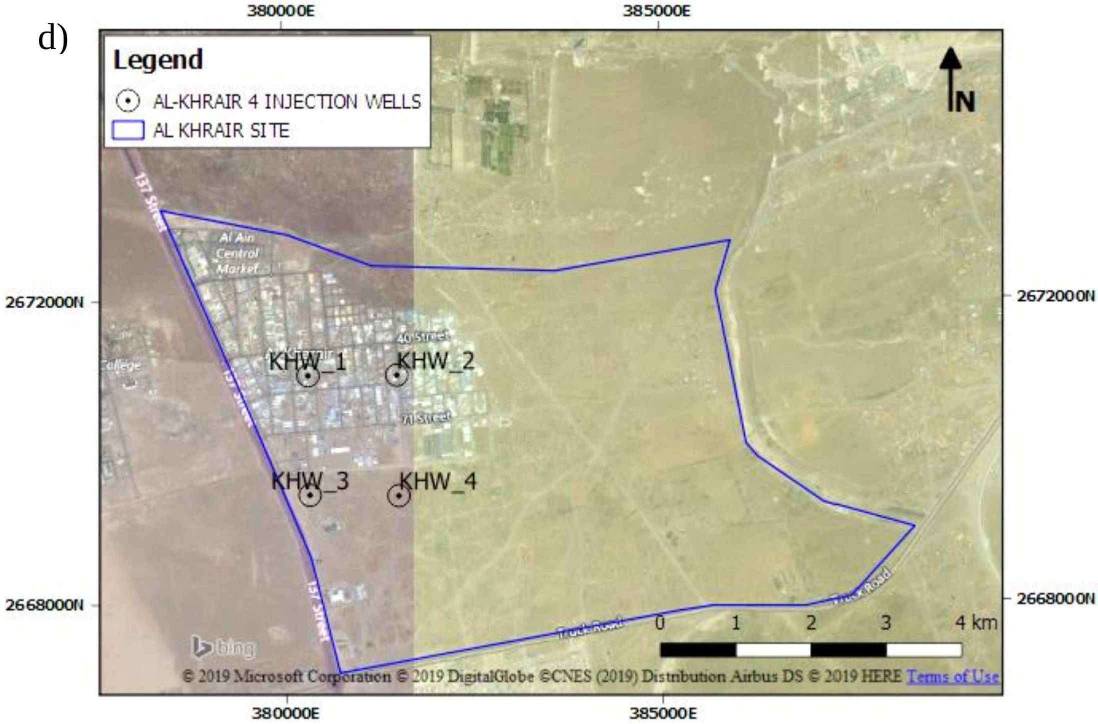


Figure 54: Closed space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

d)



e)

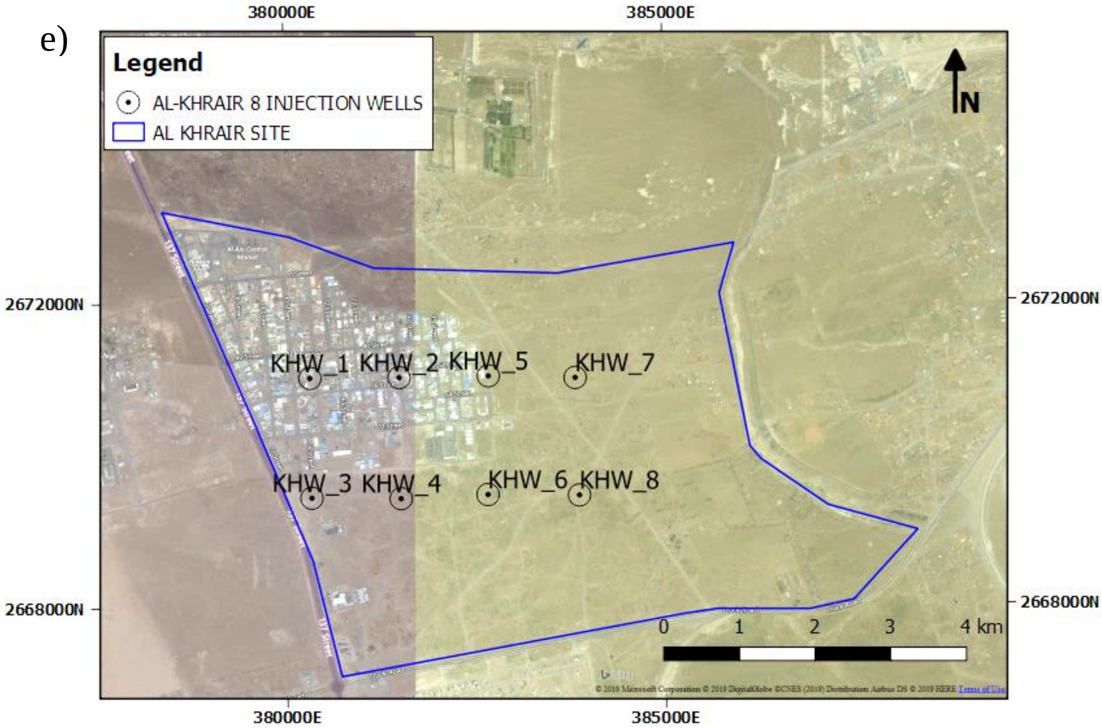


Figure 54: Closed space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

f)

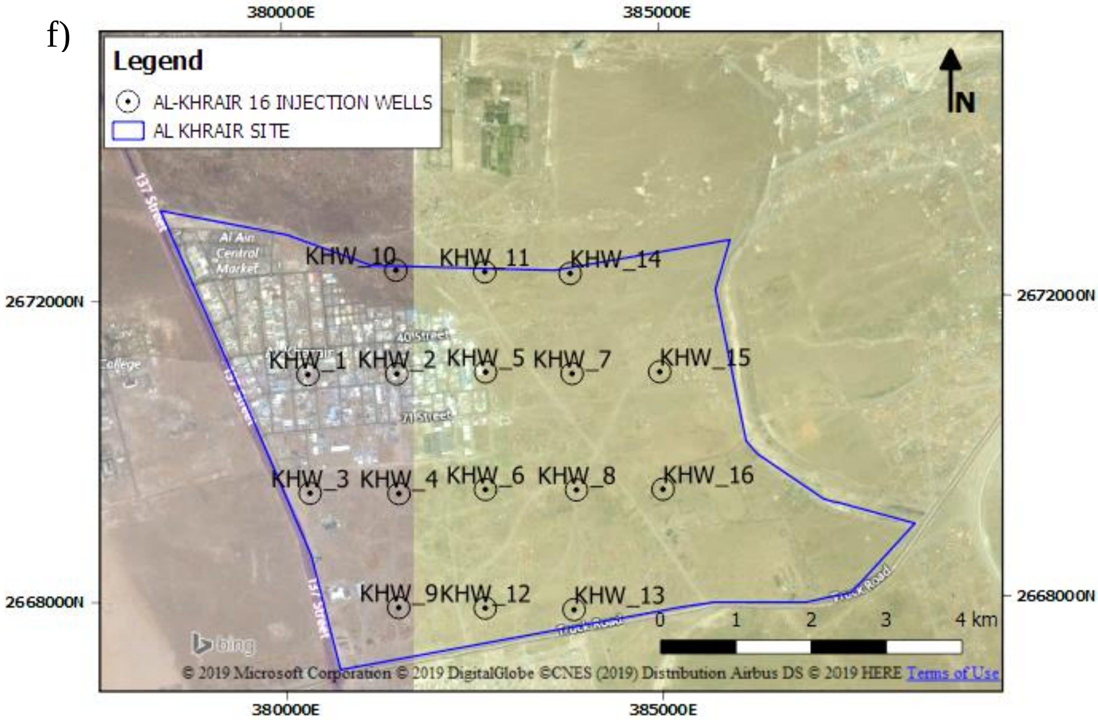


Figure 54: Closed space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

In these scenarios, the model was simulated from year 2013 until 2030 with water recharge rate of 1,000 m^3/day and 4,000 m^3/day through sixteen (16) injection wells, 4,000 m^3/day and 8,000 m^3/day through eight (08) injection wells, and 4,000 m^3/day through four (04) injection wells located at each selected site. The obtained simulated heads shows a significant increase in water head especially in recharge rate of 4,000 m^3/day and 8,000 m^3/day. The reason of this excessive rise in hydraulic head is the interference of the multiple injection wells with each other as each well will develop a reverse cone of depression that will overlap together and form a greater reverse cone of depression and reducing the drawdown at the site (Peirce et al., 1998).

The result of each scenario obtained from closed space injection wells distribution is presented in Figure 55.

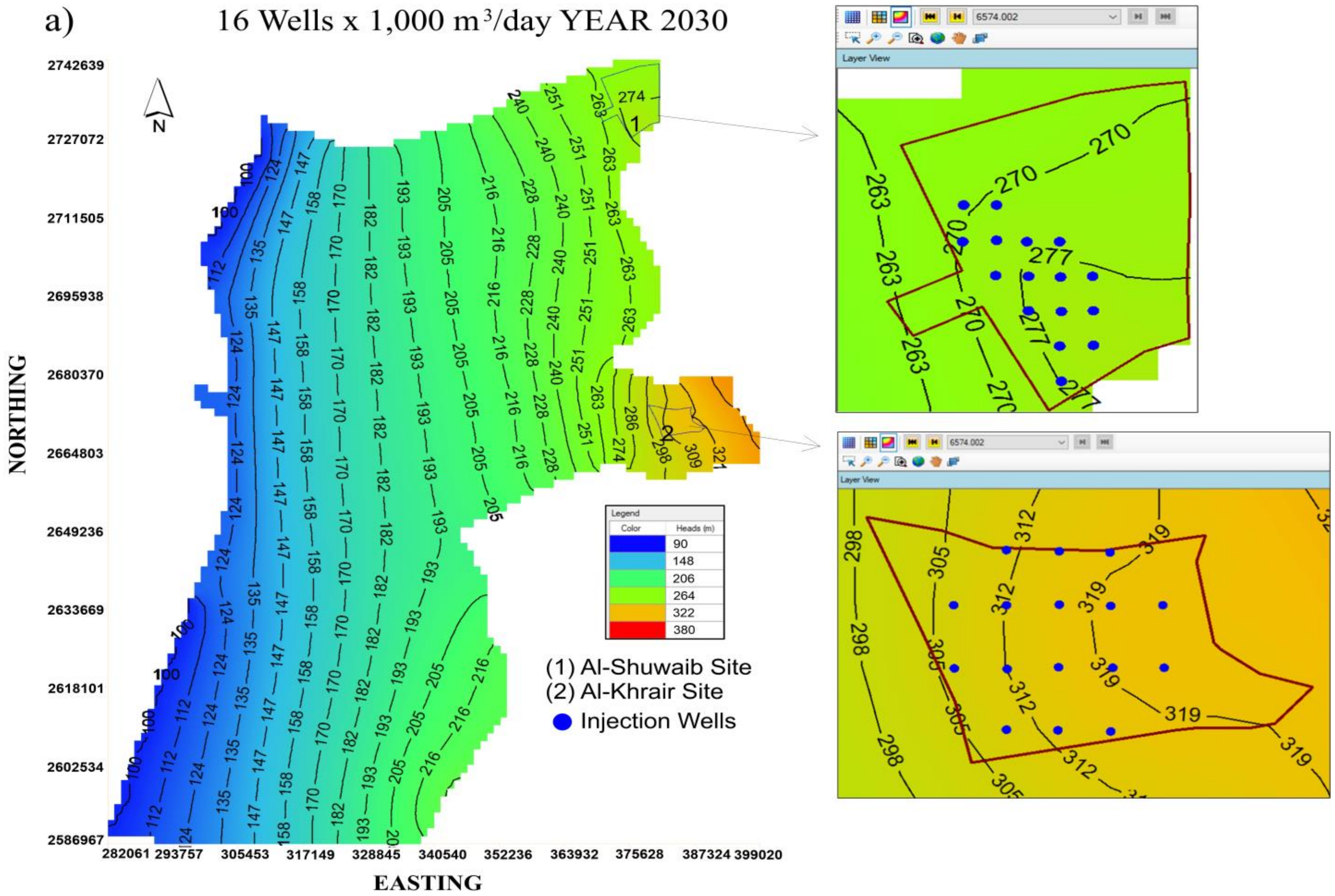


Figure 55: Obtained simulated heads from closed space injection wells distribution scenarios in 2030 a) 16 wells x 1,000 m^3/day b) 16 wells x 4,000 m^3/day c) 8 wells x 4,000 m^3/day d) 8 wells x 8,000 m^3/day e) 4 wells x 8,000 m^3/day

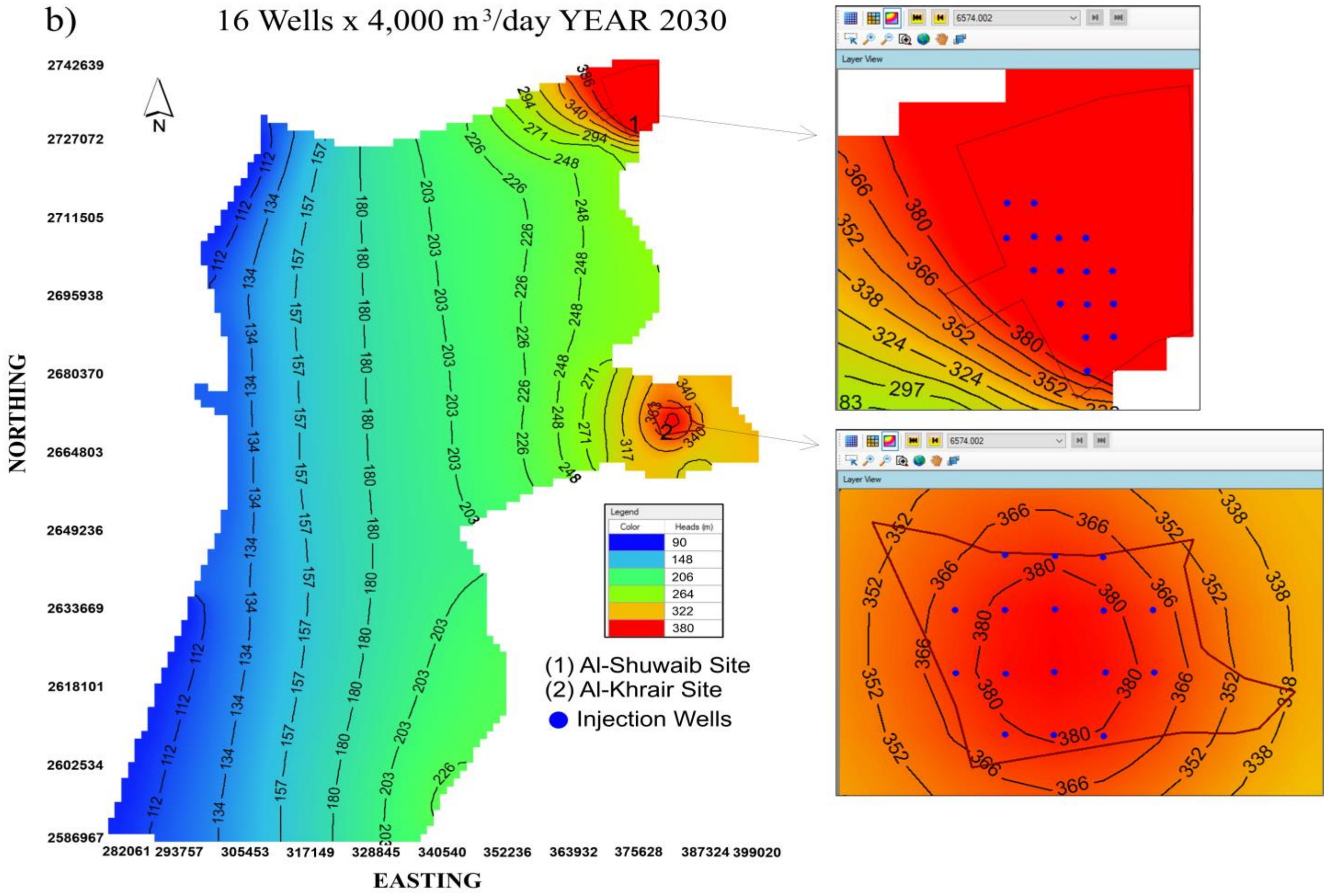


Figure 55: Obtained simulated heads from closed space injection wells distribution scenarios in 2030 a) 16 wells x 1,000 m^3/day b) 16 wells x 4,000 m^3/day c) 8 wells x 4,000 m^3/day d) 8 wells x 8,000 m^3/day e) 4 wells x 8,000 m^3/day (Continued)

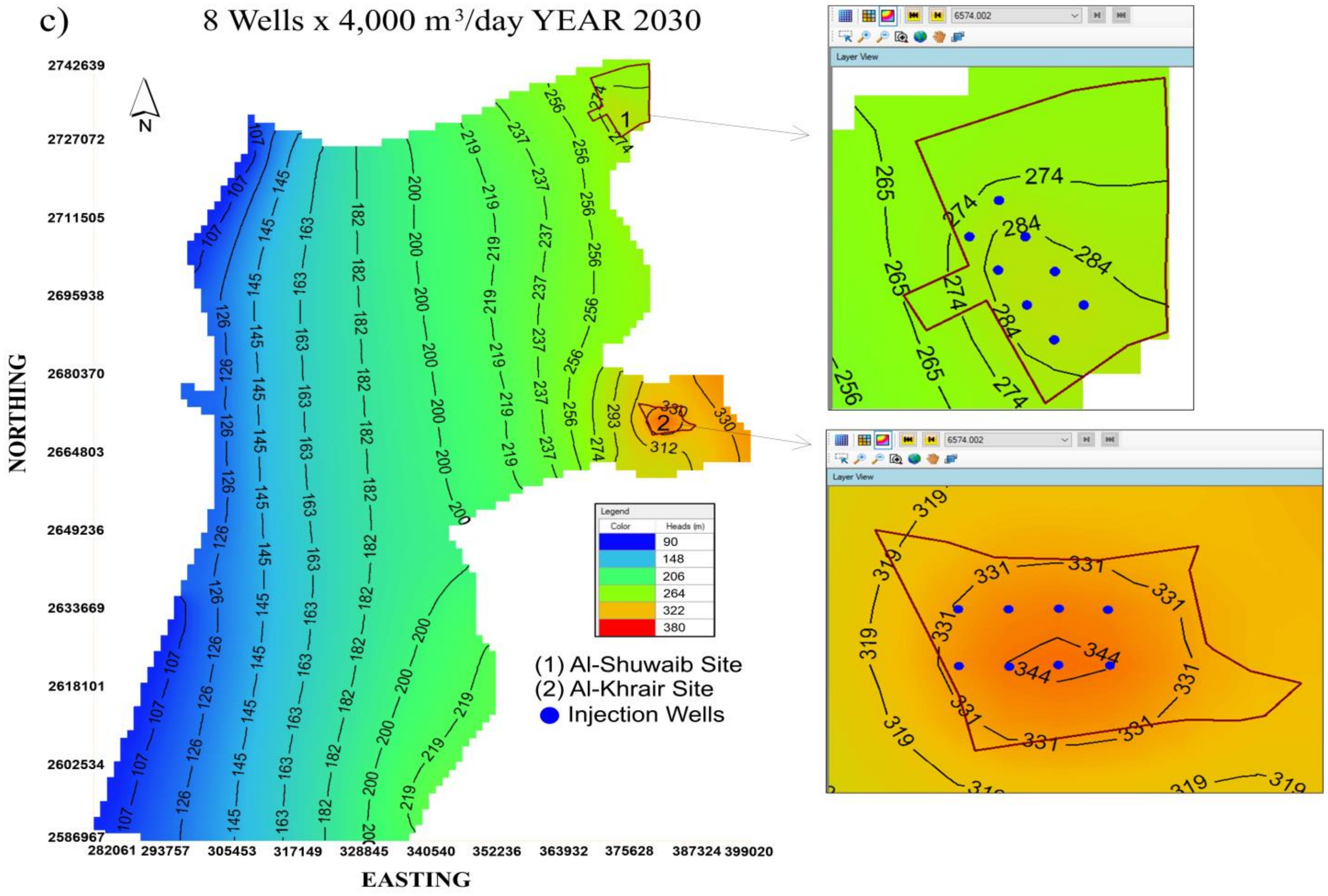


Figure 55: Obtained simulated heads from closed space injection wells distribution scenarios in 2030 a) 16 wells x 1,000 m^3/day b) 16 wells x 4,000 m^3/day c) 8 wells x 4,000 m^3/day d) 8 wells x 8,000 m^3/day e) 4 wells x 8,000 m^3/day (Continued)

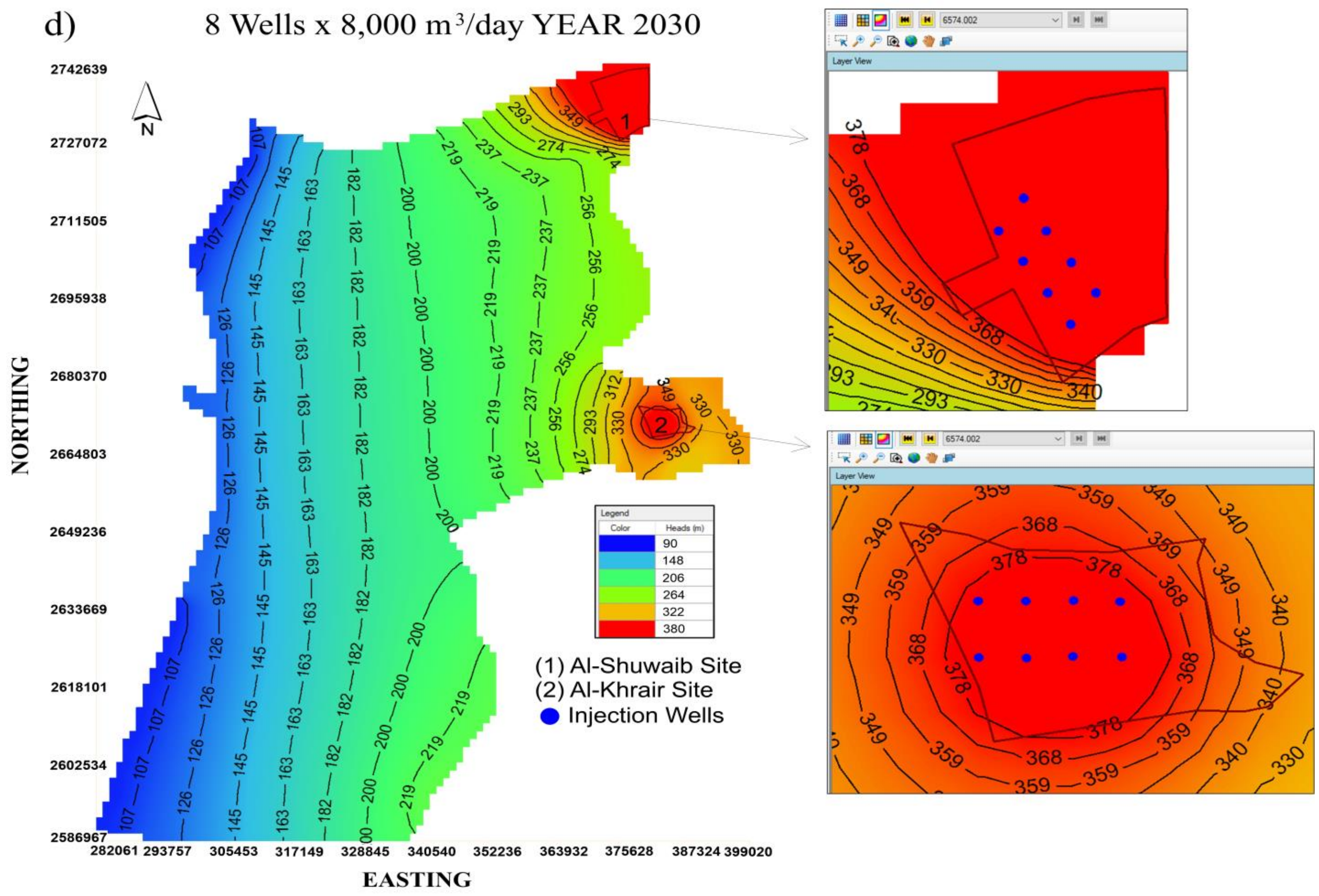


Figure 55: Obtained simulated heads from closed space injection wells distribution scenarios in 2030 a) 16 wells x 1,000 m^3/day b) 16 wells x 4,000 m^3/day c) 8 wells x 4,000 m^3/day d) 8 wells x 8,000 m^3/day e) 4 wells x 8,000 m^3/day (Continued)

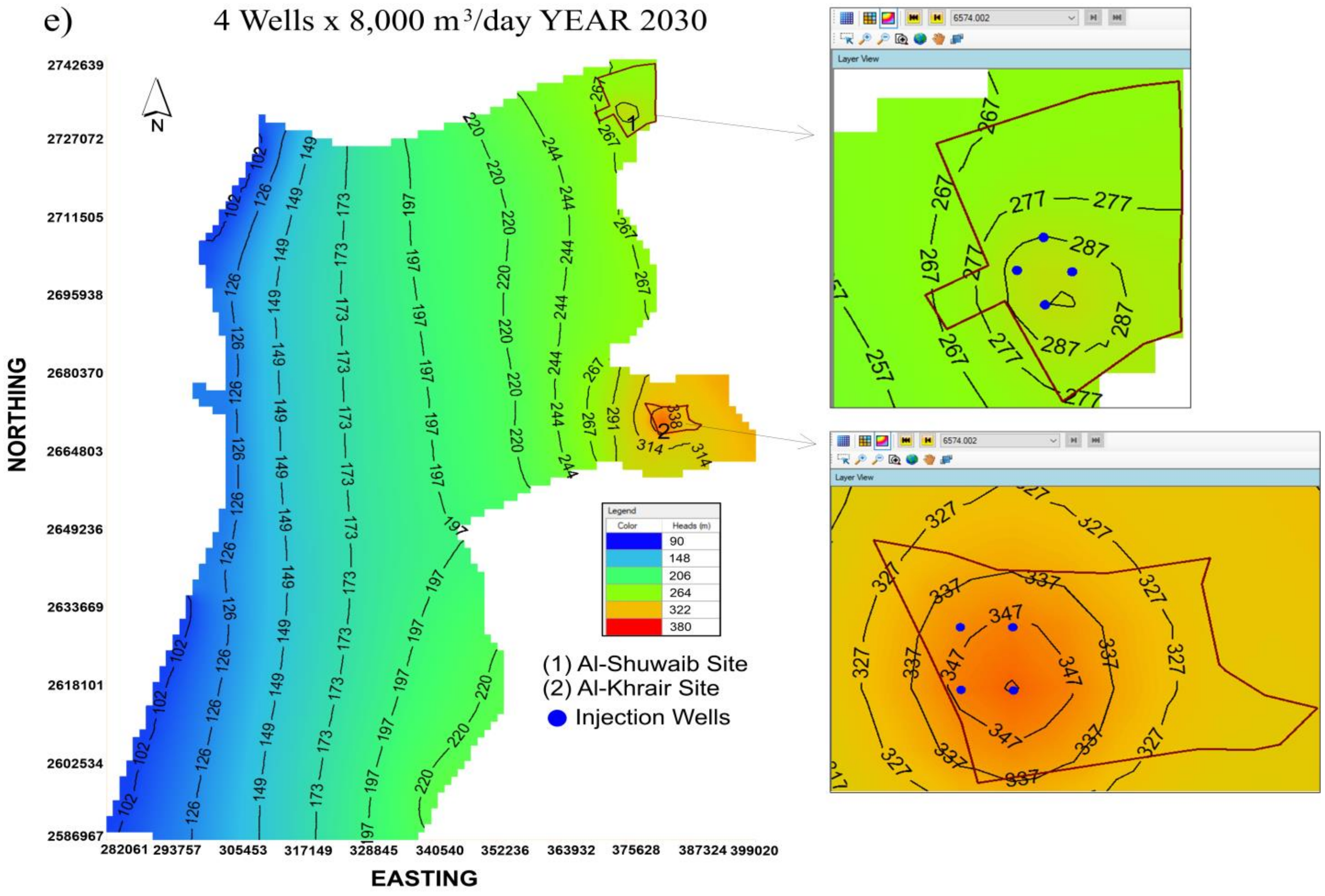


Figure 55: Obtained simulated heads from closed space injection wells distribution scenarios in 2030 a) 16 wells x 1,000 m^3/day b) 16 wells x 4,000 m^3/day c) 8 wells x 4,000 m^3/day d) 8 wells x 8,000 m^3/day e) 4 wells x 8,000 m^3/day (Continued)

From the above figures, a significant head rise in all the scenarios except the scenario of recharge rate 1,000 m^3/day is presented and mostly attributed to the close injection wells from each other which result in an overlap between each reverse cone of depression causing increase in the hydraulic head at each site.

To overcome the excessive rise in hydraulic head, a new distribution of injection wells was assigned to the site with wider space to avoid the overlap and interference of the reverse cone of depression developed at each well. The wide space injection wells has distance of more than 1,200 m. The wide space injection wells distribution is presented in Figure 56.

a)

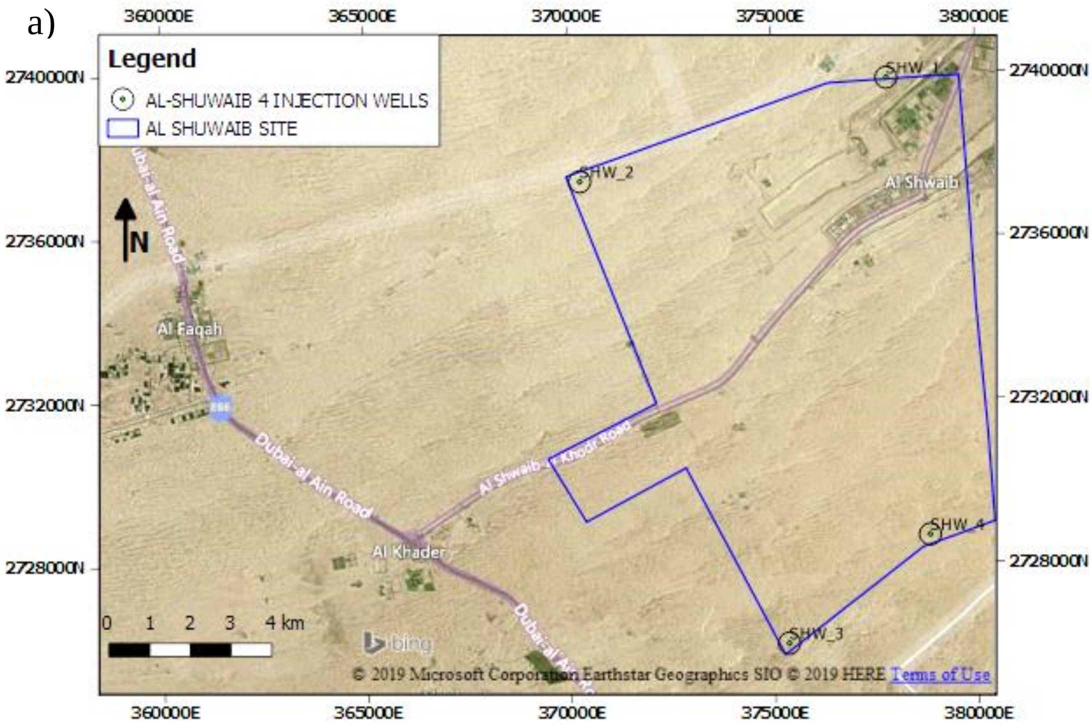
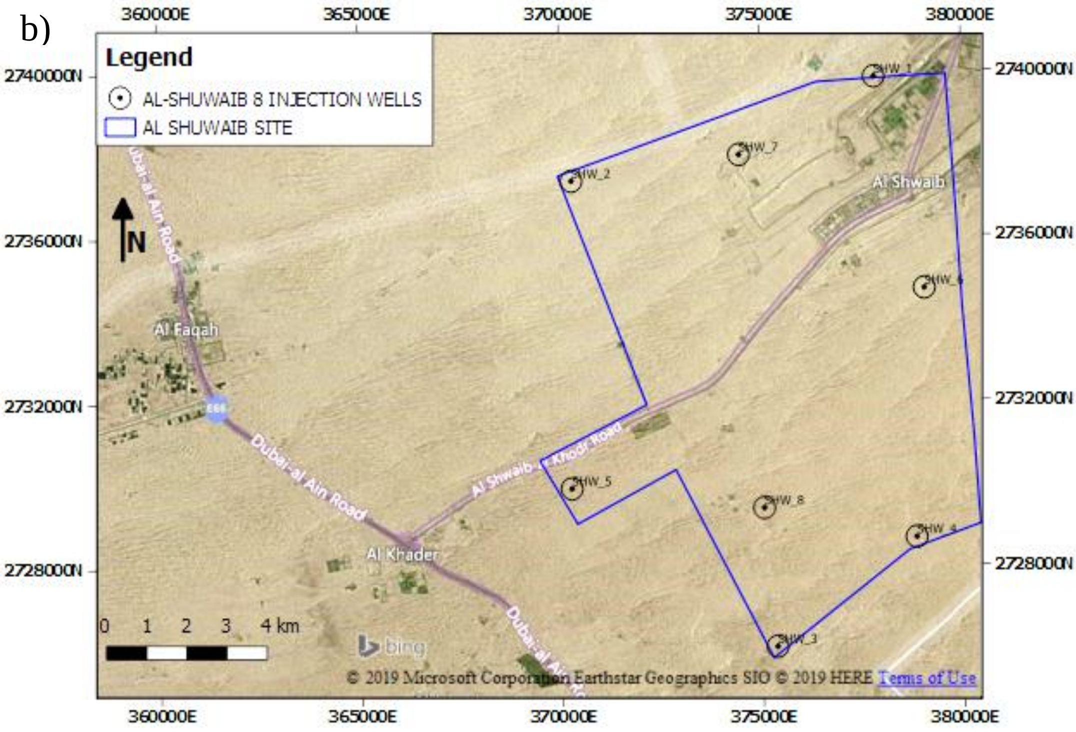


Figure 56: Wide space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells

b)



c)

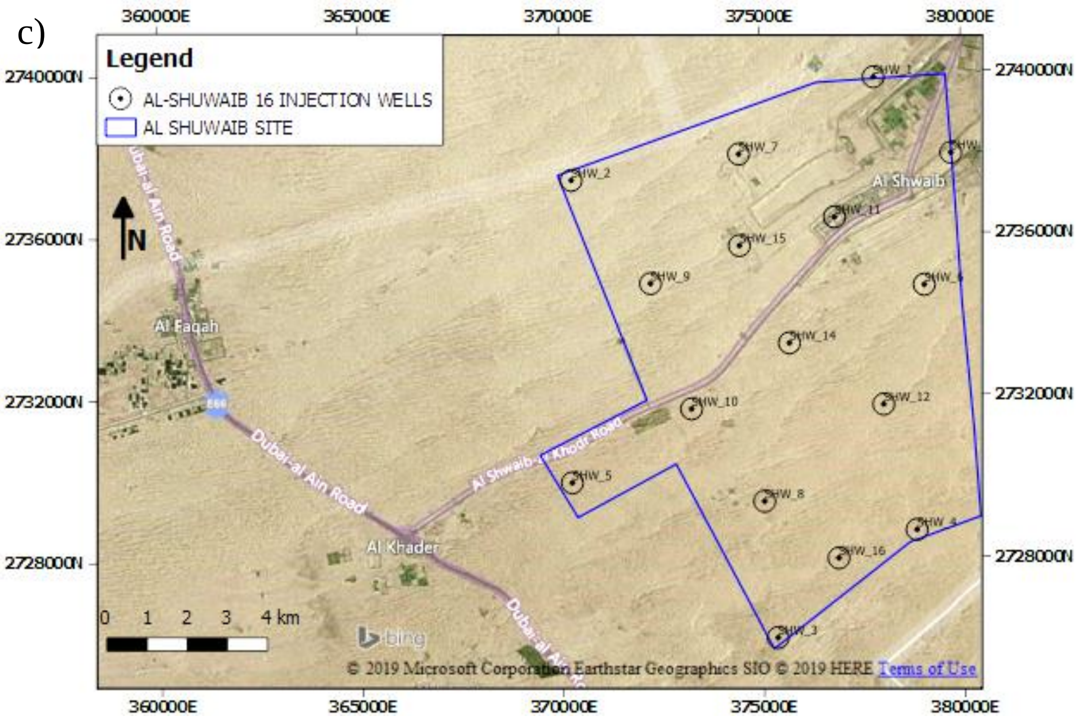
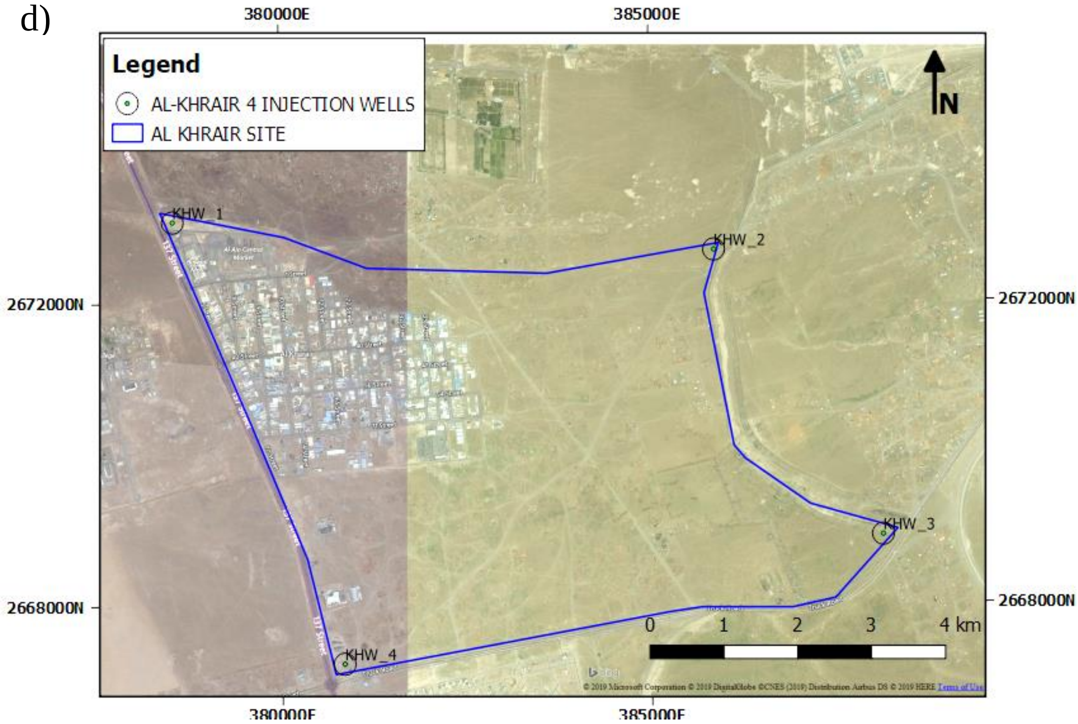


Figure 56: Wide space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

d)



e)

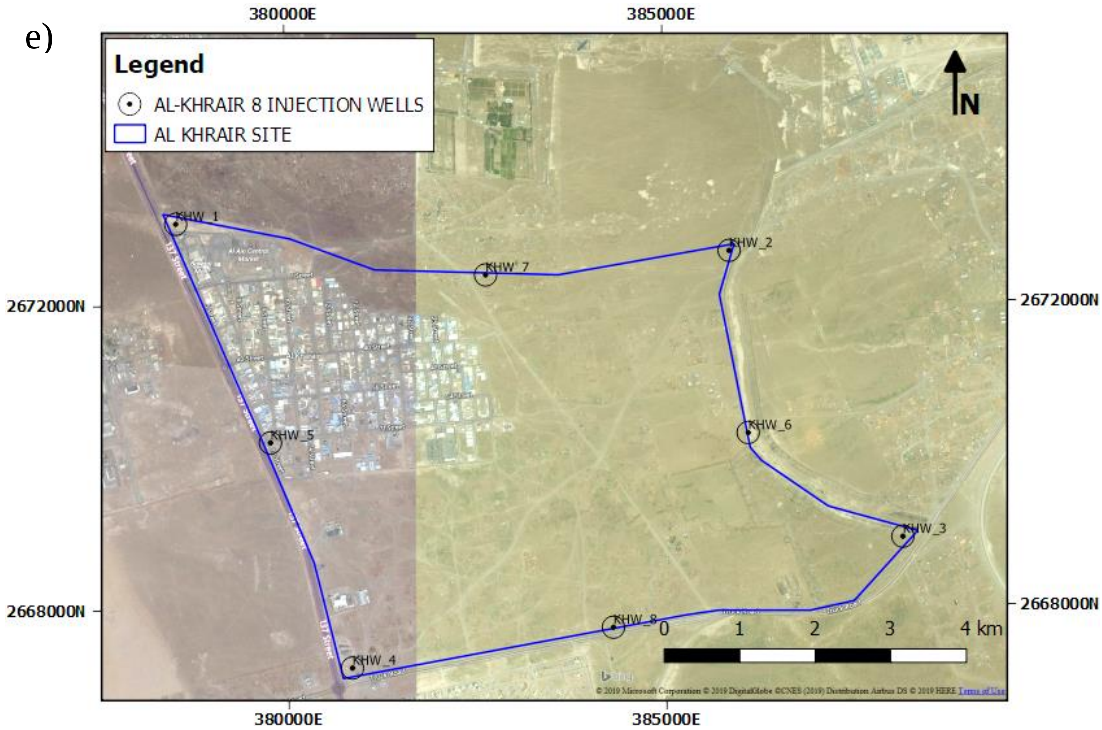


Figure 56: Wide space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

f)

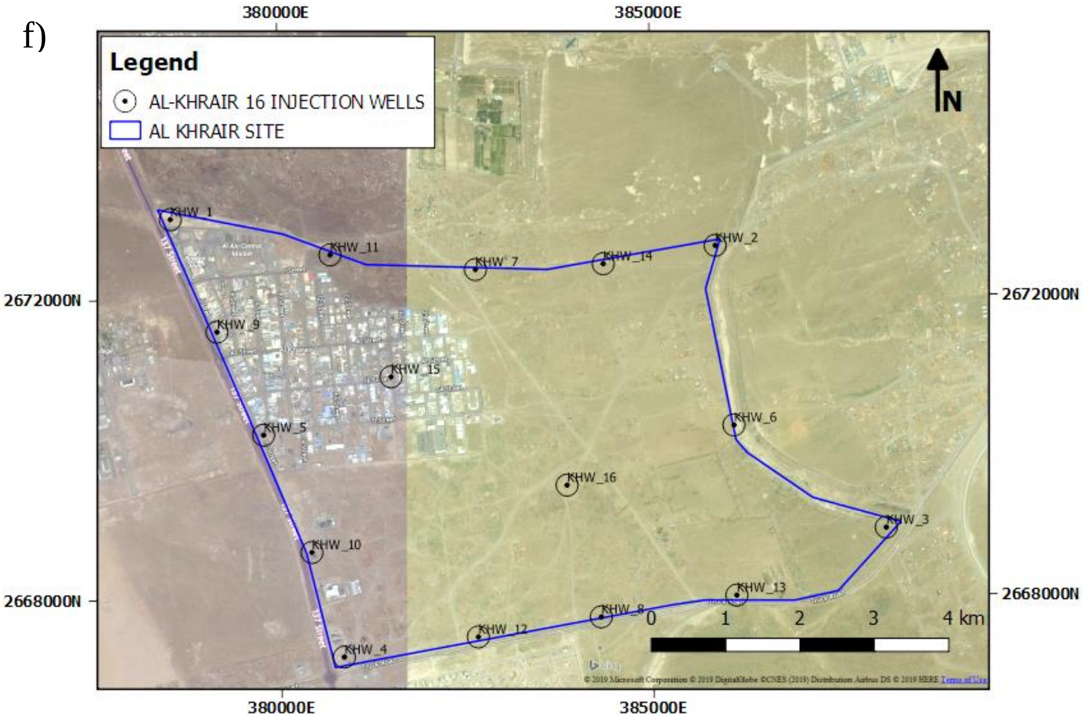


Figure 56: Wide space injection wells distribution a) Al-Shuwaib 4 injection wells, b) Al-Shuwaib 8 injection wells, c) Al-Shuwaib 16 injection wells, d) Al-Khrair 4 injection wells, e) Al-Khrair 8 injection wells, and f) Al-Khrair 16 injection wells (Continued)

The new injection wells distribution was considered in the further assessment of the Al-Khrair and Al-Shuwaib sites. In these scenario, the model was simulated from year 2013 until 2030 with water recharge rate of 1,000 m^3/day and 4,000 m^3/day through sixteen (16) injection wells, 4,000 m^3/day and 8,000 m^3/day through eight (08) injection wells, and 4,000 m^3/day through four (04) injection wells located within the boundary of Al-Khrair and Al-Shuwaib sites. The aim was to examine which one of the sites can be recharge with the surplus desalinated water in Abu Dhabi Emirates that was estimated around 64,000 m^3/day. Thus, five (05) ASR scenarios were developed with three main water recharge rates of 16,000 m^3/day, 32,000 m^3/day, and 64,000 m^3/day using multiple injection wells to simulate the hydraulic heads at Al-Khrair and Al-Shuwaib sites as listed in Table 28.

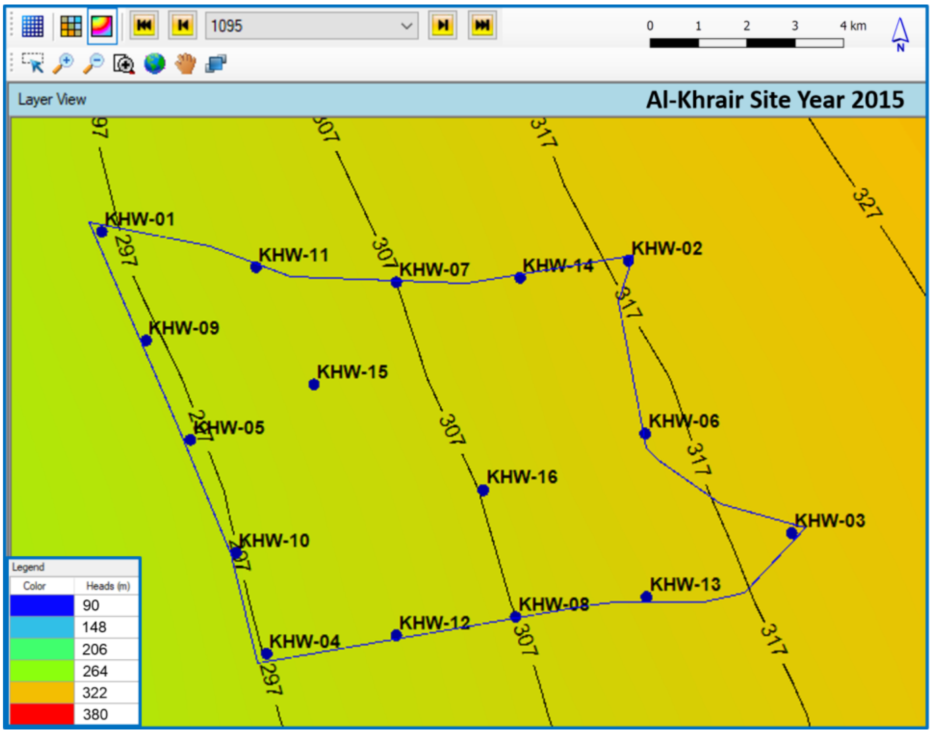
Table 28: The simulated ASR scenarios per site along with the total recharge rate (m^3/day)

Scenario	Number of wells per Site	Recharge Rate (m^3/day)	Total Recharge Rate (m^3/day)
1	16	1,000	16,000
2	4	8,000	32,000
3	8	4,000	32,000
4	8	8,000	64,000
5	16	4,000	64,000

6.2.2 ASR Scenario 1 (Recharge Rate 16,000 m^3/day)

In this scenario, the model was simulated with total water recharge rate of 16,000 m^3/day from year 2015 until 2030 through 16 injection wells located at each selected site. Wide spacing between injection wells was considered while distributing the wells within the boundary of each site to avoid excessive head build-up. For the injection wells, KHW was named for Al-Khrair wells while SHW was named for Al-Shuwaib wells. The results of each site are presented in Figures 57 and 58.

a)



b)

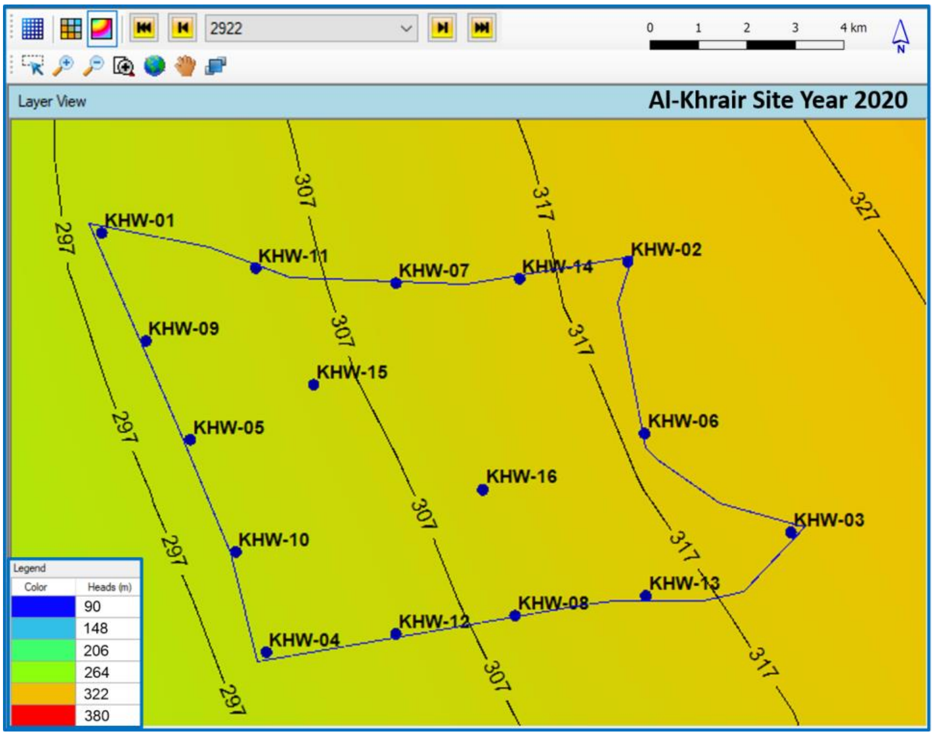
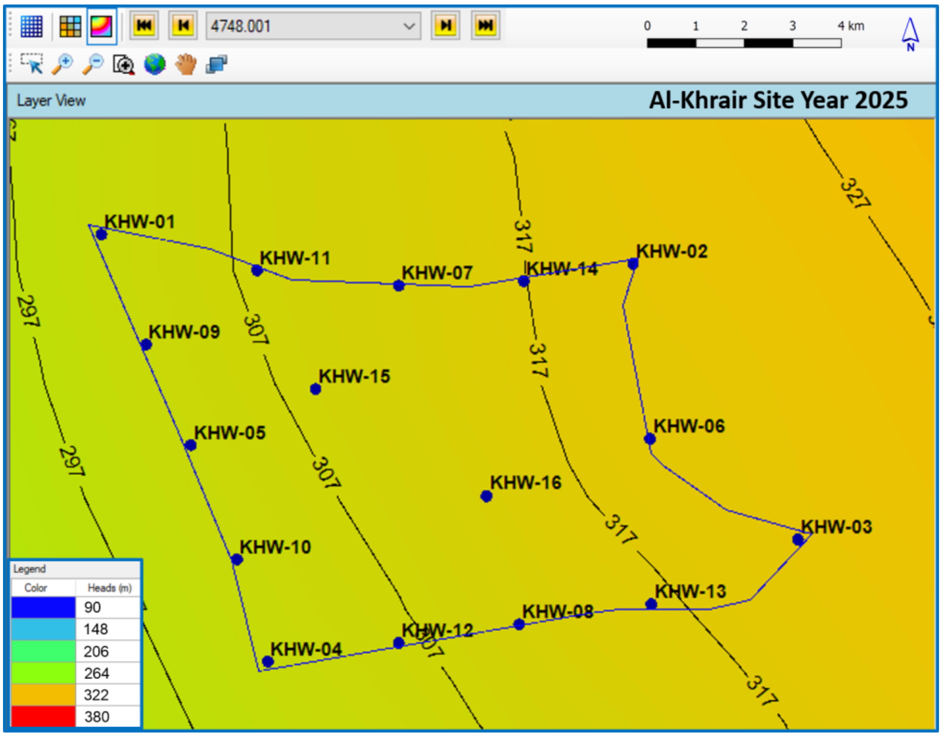


Figure 57: ASR scenario 1 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site

c)



d)

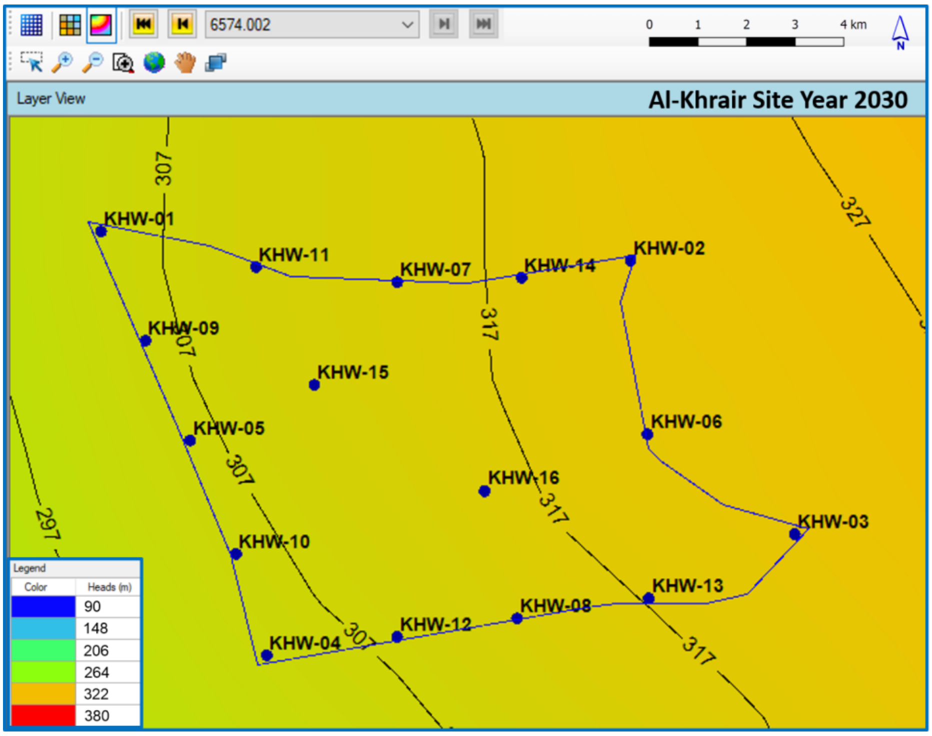
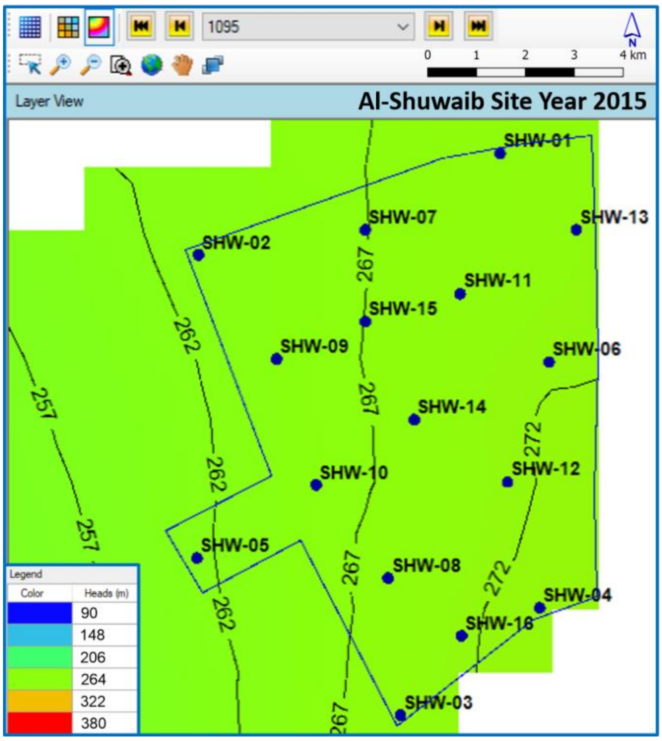


Figure 57: ASR scenario 1 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

a)



b)

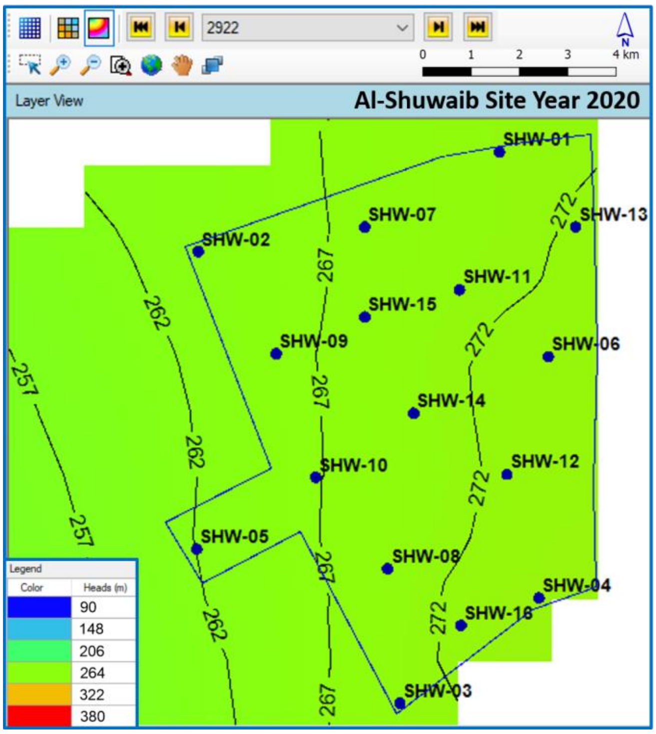
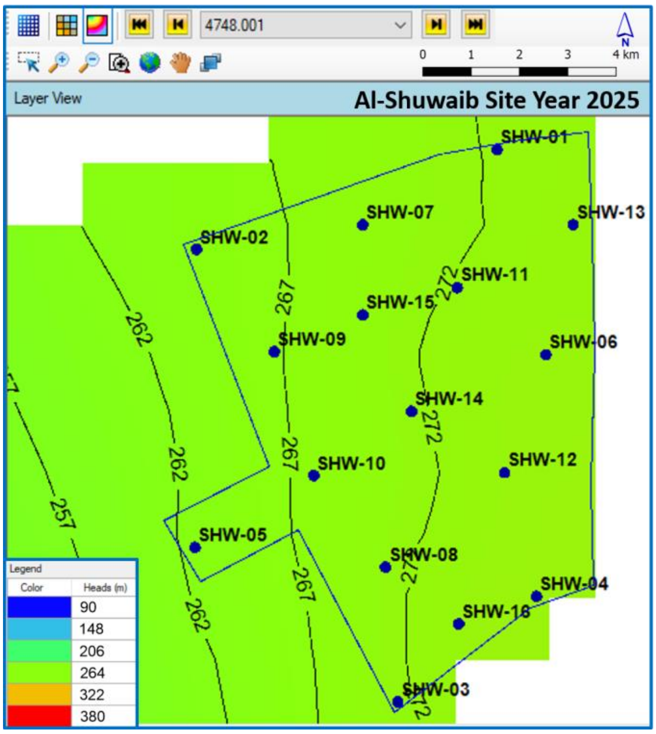


Figure 58: ASR scenario 1 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site

c)



d)

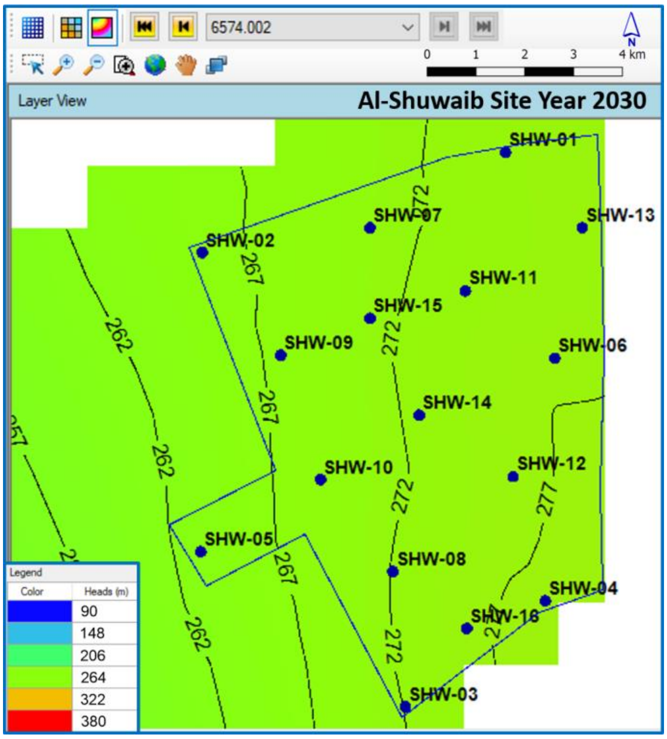


Figure 58: ASR scenario 1 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

From the above results, the hydraulic head in Al-Khrair site has increased from 297 m in 2015 at the west of the site to around 307 m in 2030 while the eastern part of the site has increased from 317 m in 2015 to around 320 m in 2030. For Al-Shuwaib Site, the hydraulic head has increased from 262 m in 2015 at the west of the site to around 267 m in 2030 while the eastern part of the site has increased from 272 m in 2015 to around 277 m in 2030.

6.2.3 ASR Scenario 2 (Recharge Rate 32,000 m^3/day)

In this scenario, the model was simulated with total water recharge rate of 32,000 m^3/day from year 2015 until 2030 through 4 injection wells (8,000 m^3/day per well) located at each selected site. The results of each site are presented in Figures 59 and 60.

a)

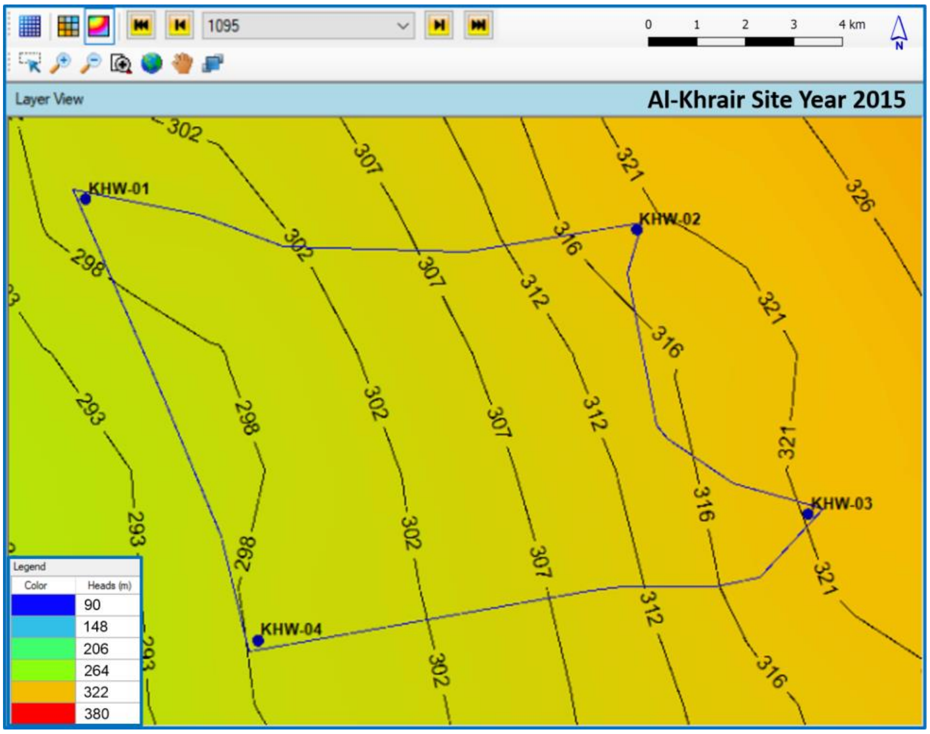
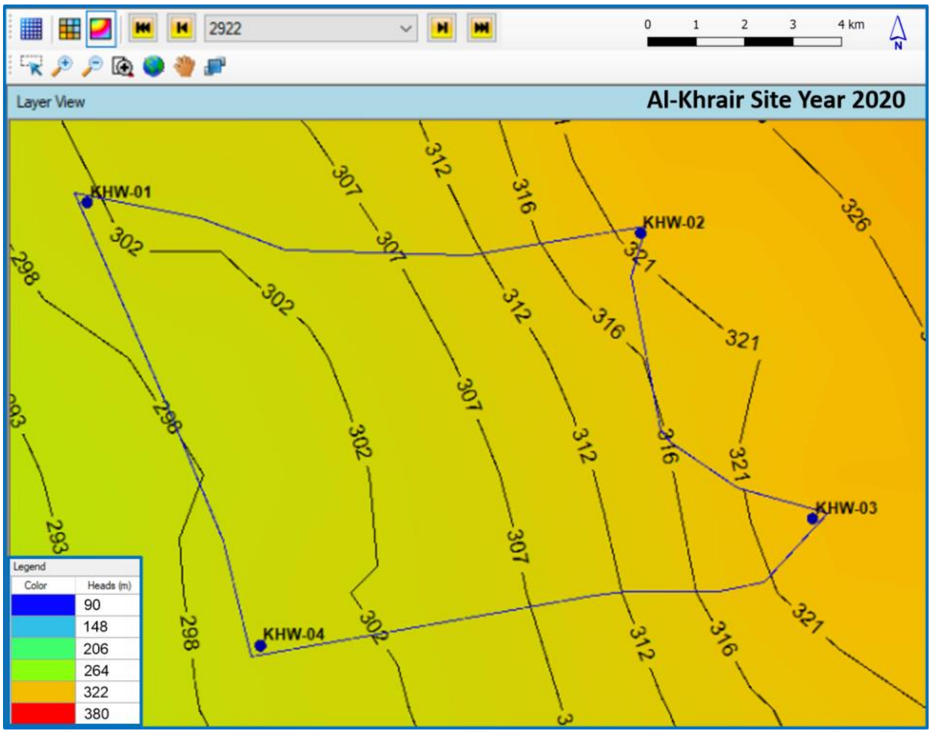


Figure 59: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site

b)



c)

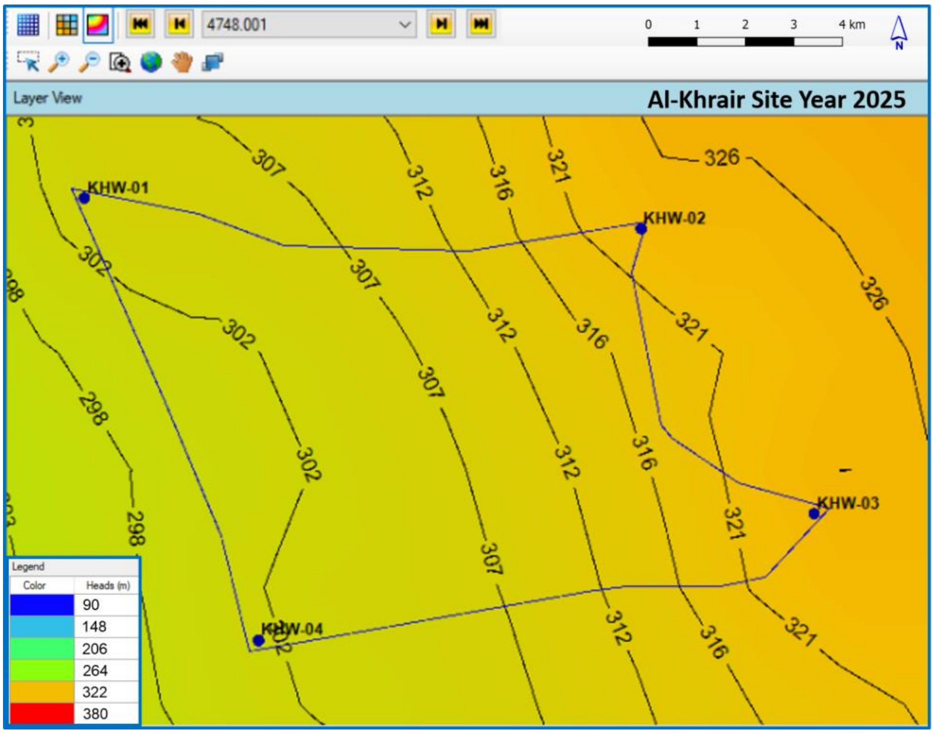


Figure 59: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

d)

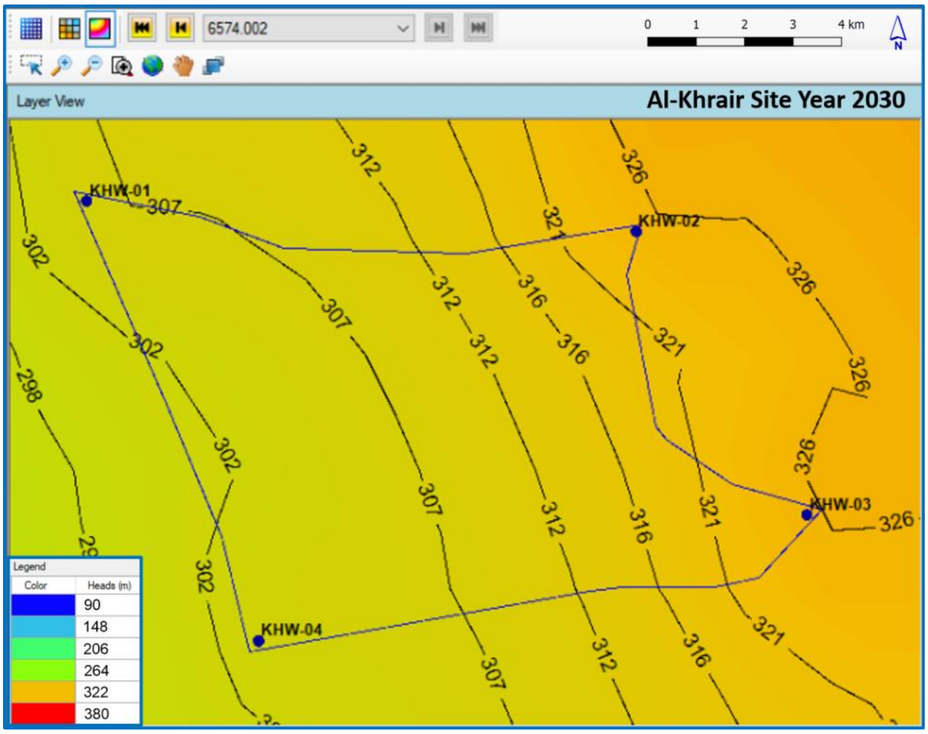


Figure 59: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

a)

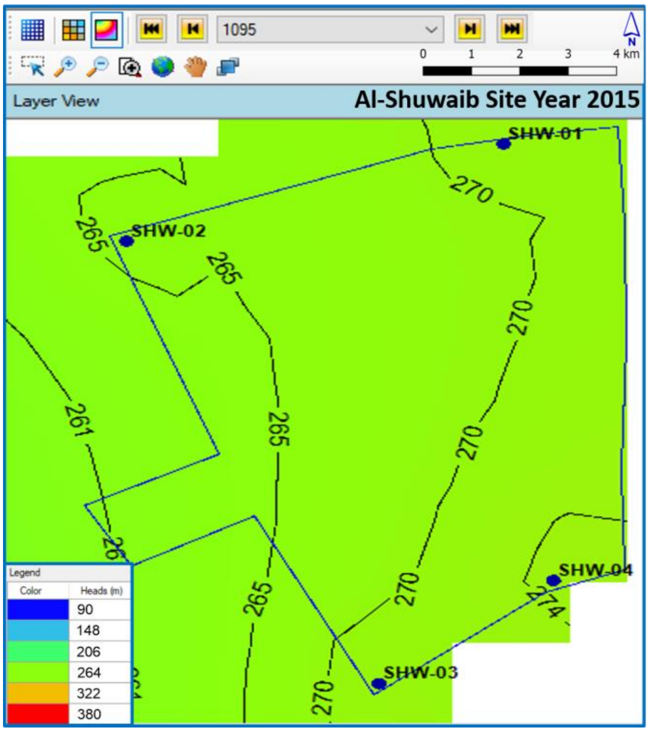
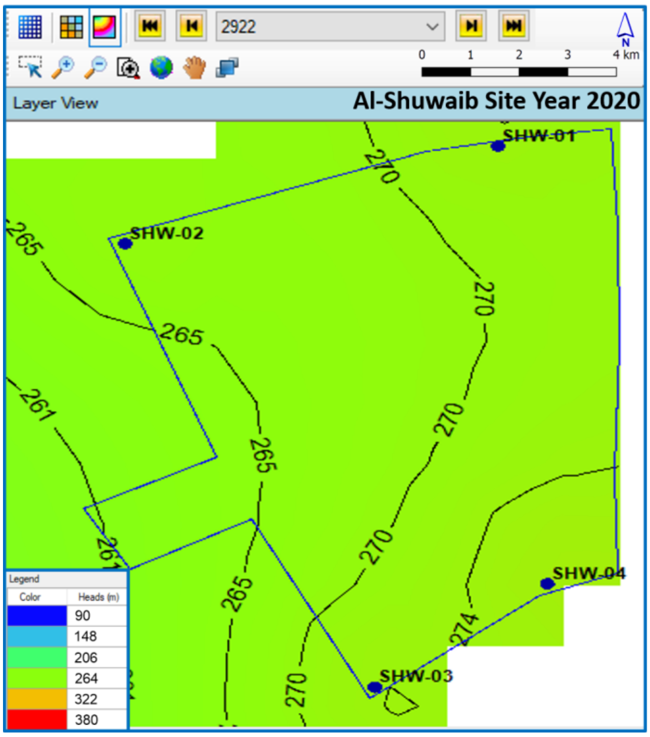


Figure 60: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site

b)



c)

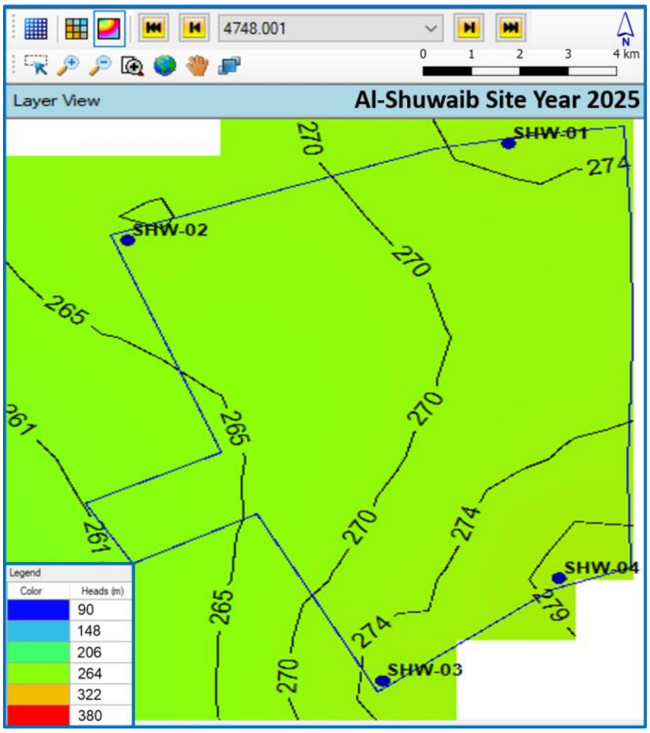


Figure 59: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

d)

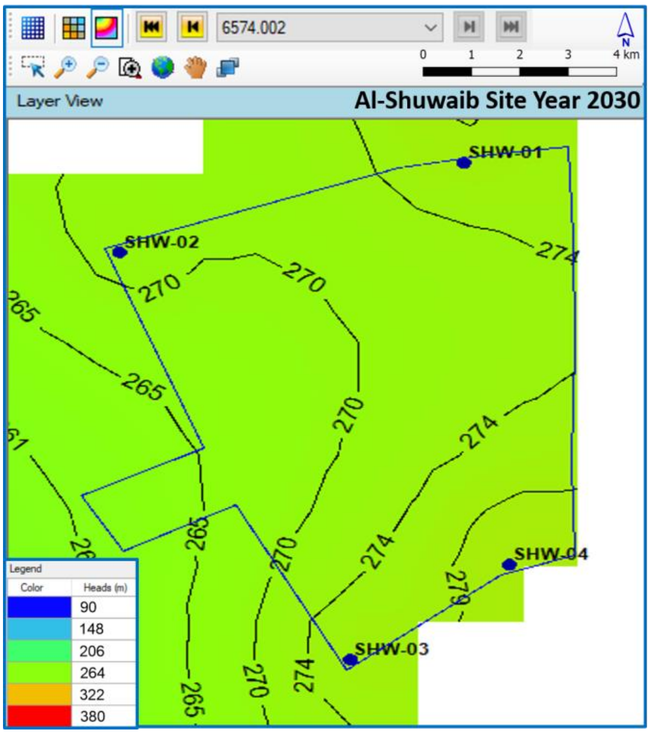


Figure 59: ASR scenario 2 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

From the above results, the hydraulic head in Al-Khrair site has increased from 298 m in 2015 at the west of the site to around 302 m in 2030 while the eastern part of the site has increased from 316 m in 2015 to around 321 m in 2030. A slight changes in the hydraulic heads has been noticed around the four injection wells located at the site boundary corners (KHW-1, KHW-2, KHW-3, and KHW-4) in 2030.

For Al-Shuwaib site, the hydraulic head has increased slightly from 2015 to 2030 with hydraulic head ranges from 274 m to 265 m flowing towards the west of the site. Minor reverse cone of depressions have been developed around the four injection wells in 2025 and increase of hydraulic head from 270 m in 2015 to 274 m in 2030 in the east part of the site was observed.

6.2.4 ASR Scenario 3 (Recharge Rate 32,000 m^3/day)

In this scenario, the model was simulated with total water recharge rate of 32,000 m^3/day from year 2015 until 2030 through 8 injection wells (4,000 m^3/day per well) located at each selected site. The results of each site are presented in Figures 61 and 62.

a)

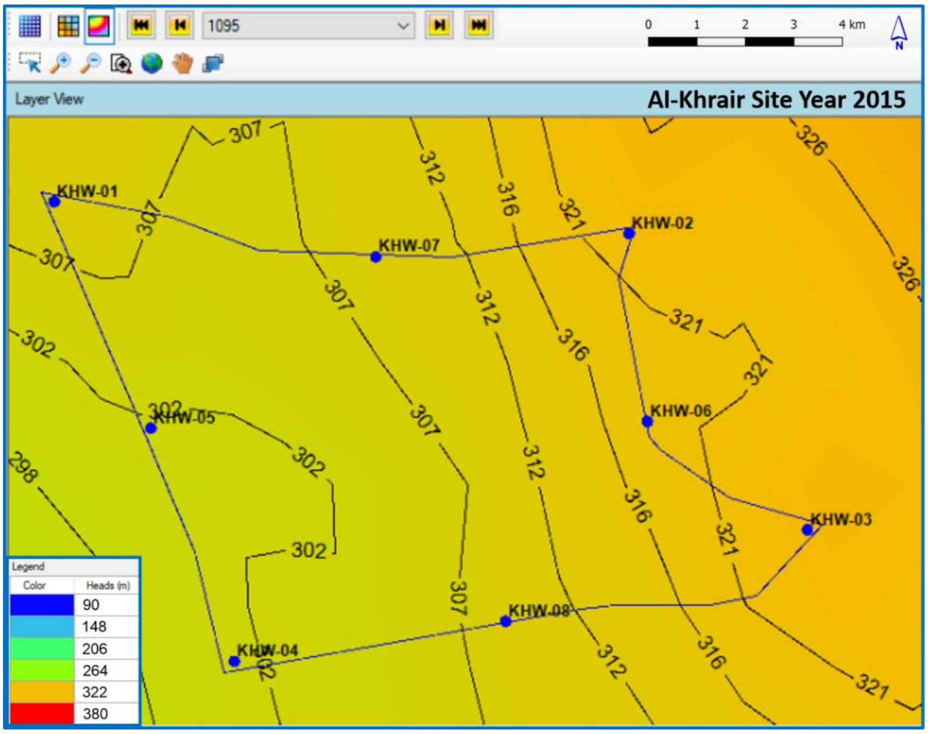
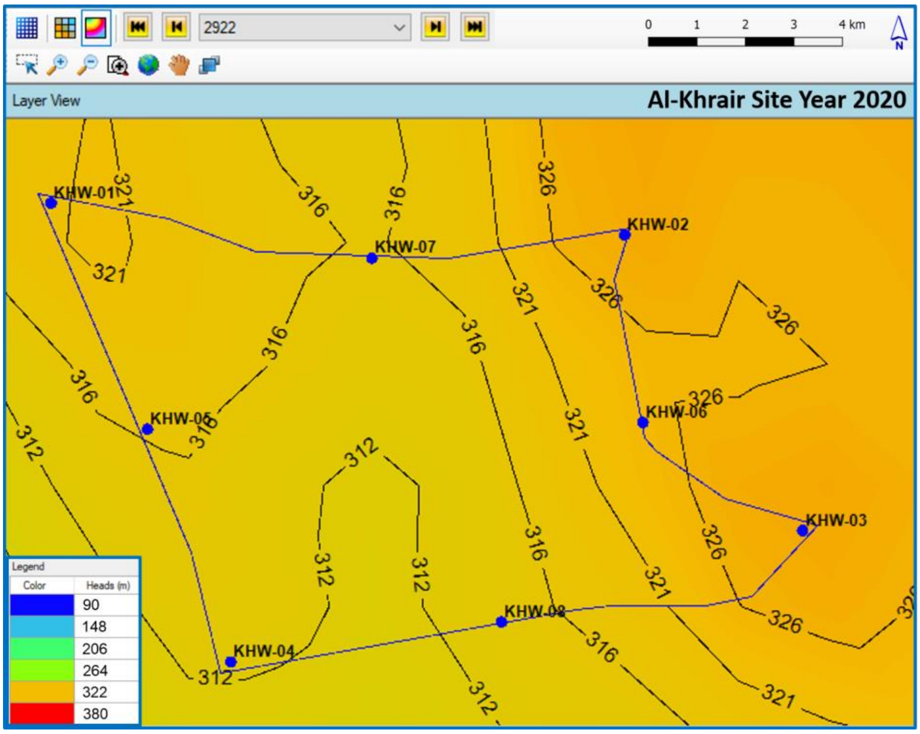


Figure 61: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site

b)



c)

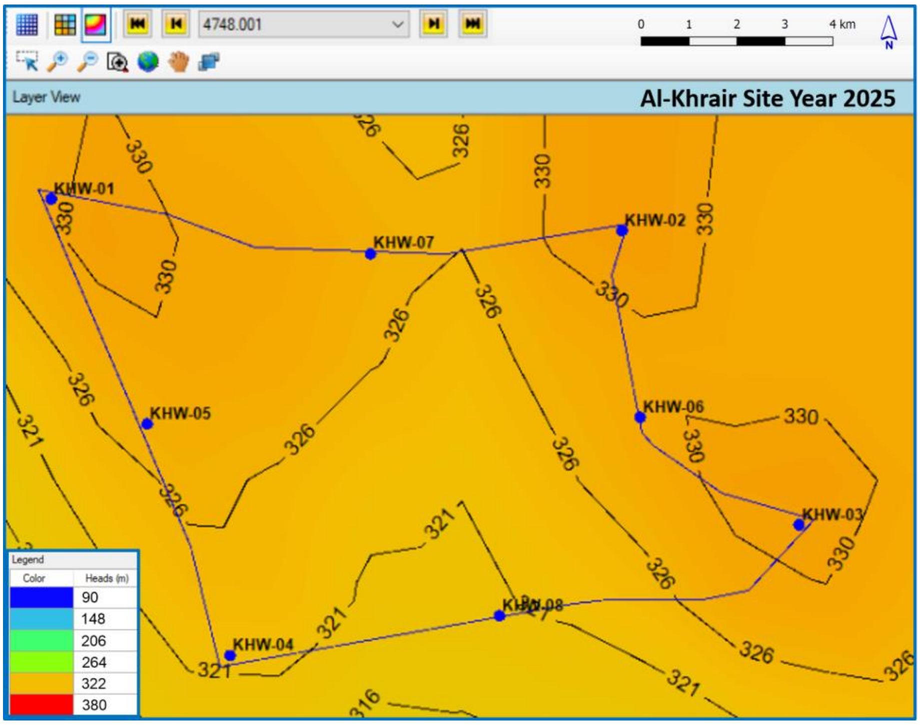


Figure 61: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

d)

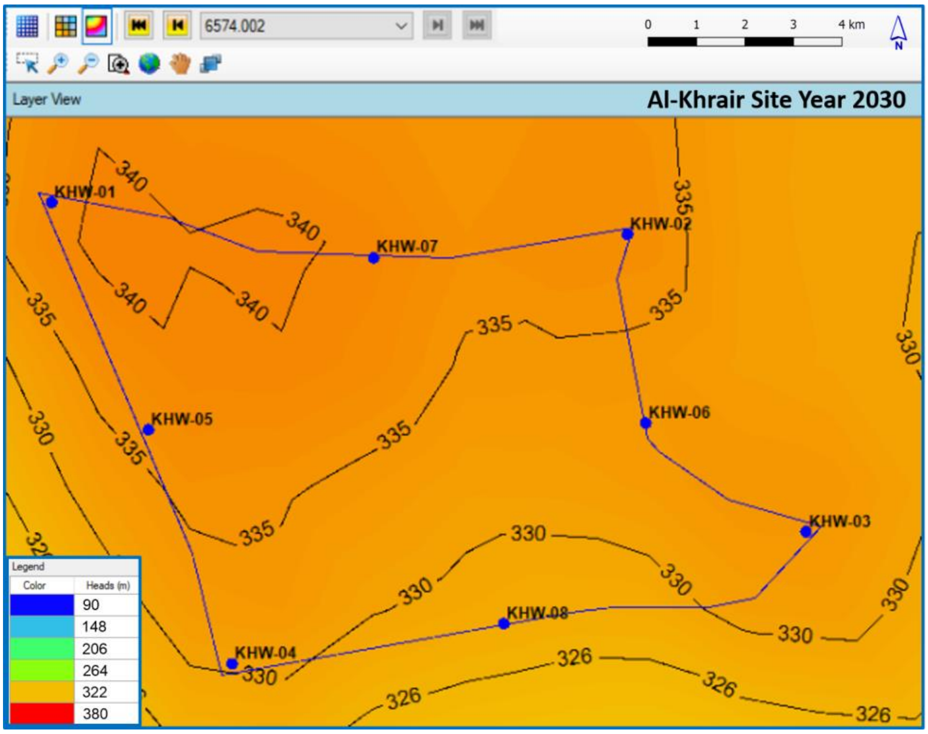


Figure 61: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

a)

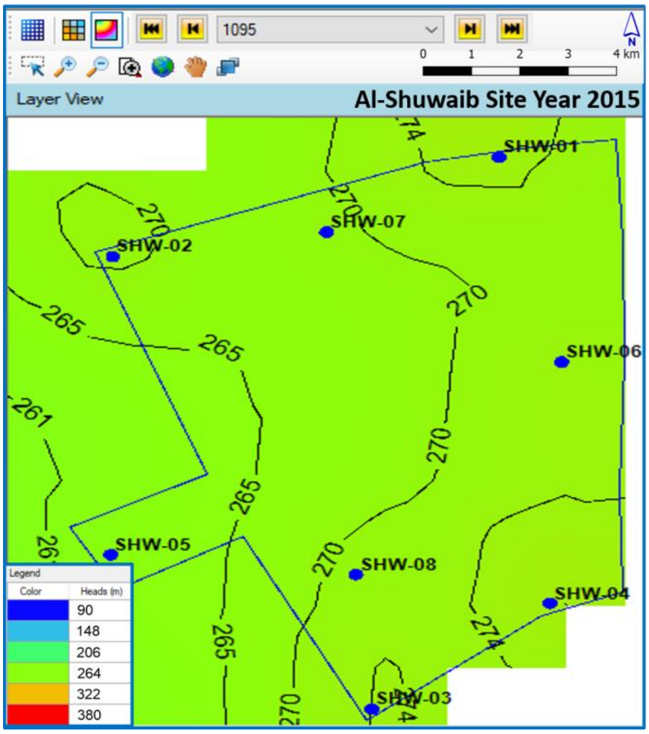
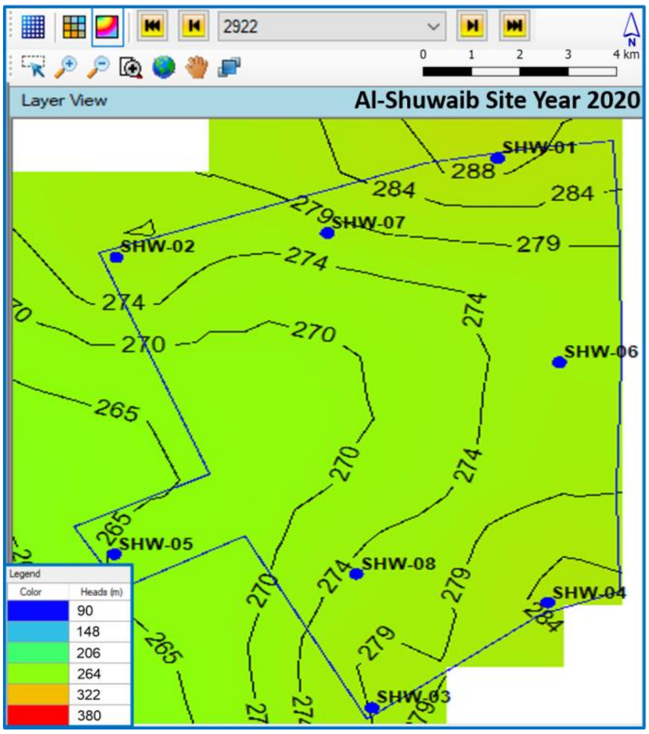


Figure 62: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site

b)



c)

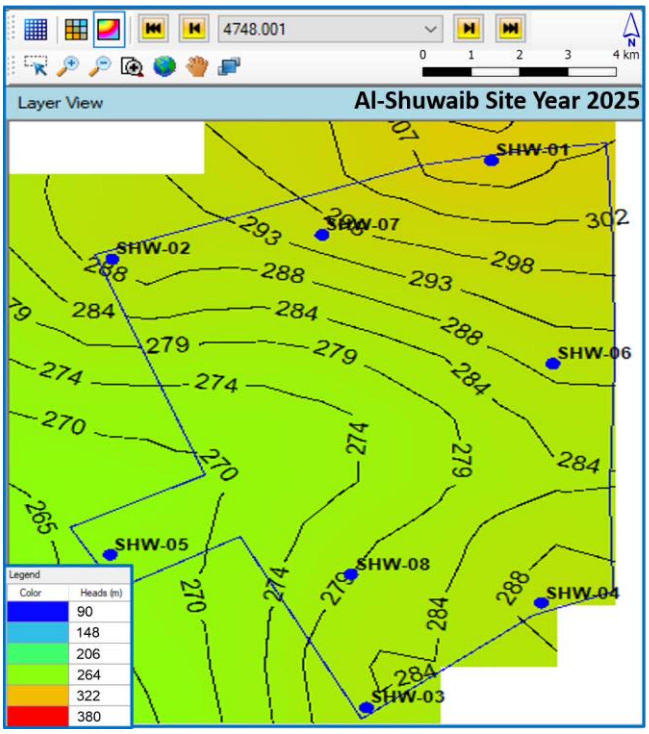


Figure 62: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

d)

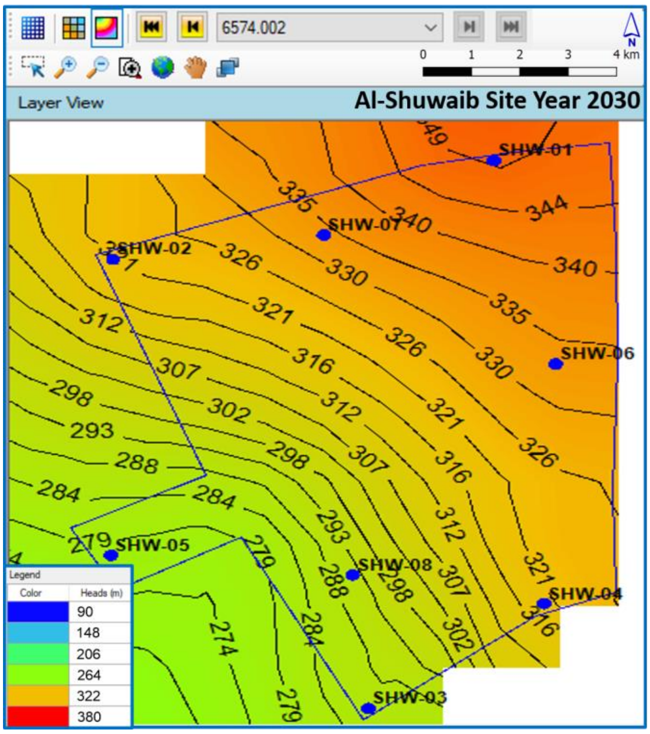


Figure 62: ASR scenario 3 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

From the above results, the hydraulic head in Al-Khrair site has increased significantly from around 307 m in 2015 at the west of the site to around 340 m in 2030 while the eastern part of the site has increased from around 320 m in 2015 to 332 m in 2030. Local reverse cone of depression has been formed around KHW-1, KHW-5, and KHW-6 in 2015. In 2020, the reverse cone of depression is formed between KHW-1 - KHW5 and KHW-4 and KHW-8 while the hydraulic head increases around KHW-6. In 2025, changes in the hydraulic head has been observed and reverse cone of depression formed towards the northwest of the site with hydraulic head 330 m until it reaches 340 m in 2030.

For Al-Shuwaib site, the hydraulic head in 2015 has increased at the location of each well forming a reverse cone of depression with hydraulic head of 274 m around

SHW-1, SHW-3, and SHW-4 and increases to 350 m in 2030. The minimum hydraulic head observed is 261 m at SHW-05 and increases to 279 m in 2030.

6.2.5 ASR Scenario 4 (Recharge Rate 64,000 m^3/day)

In this scenario, the model was simulated with total water recharge rate of 64,000 m^3/day from year 2015 until 2030 through 16 injection wells (4,000 m^3/day per well) located at each selected site. The results of each site are presented in Figures 63 and 64.

a)

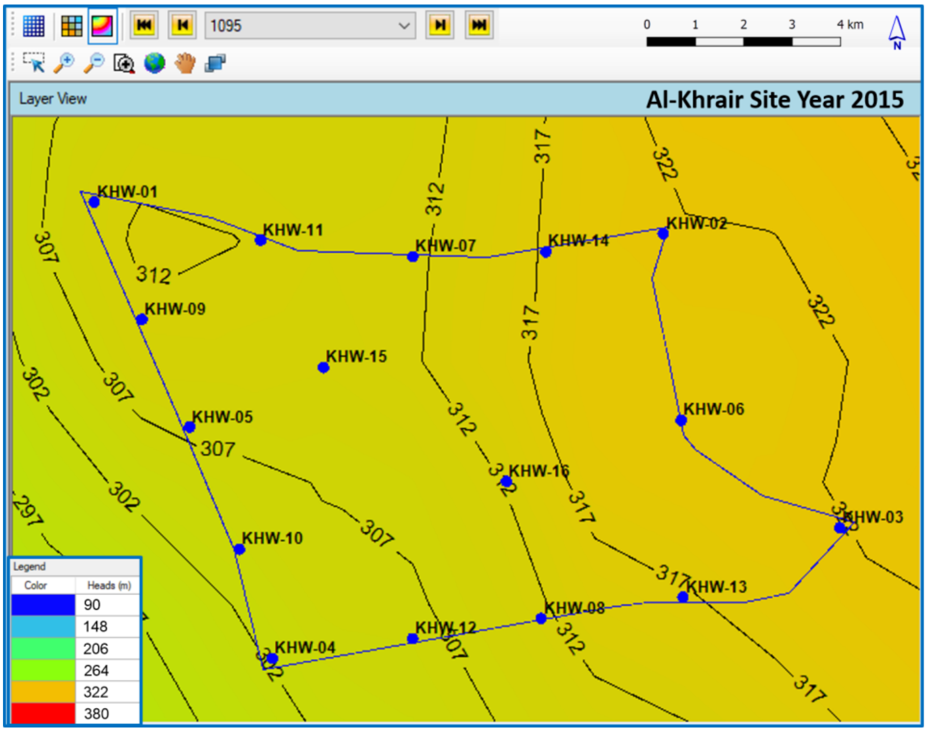
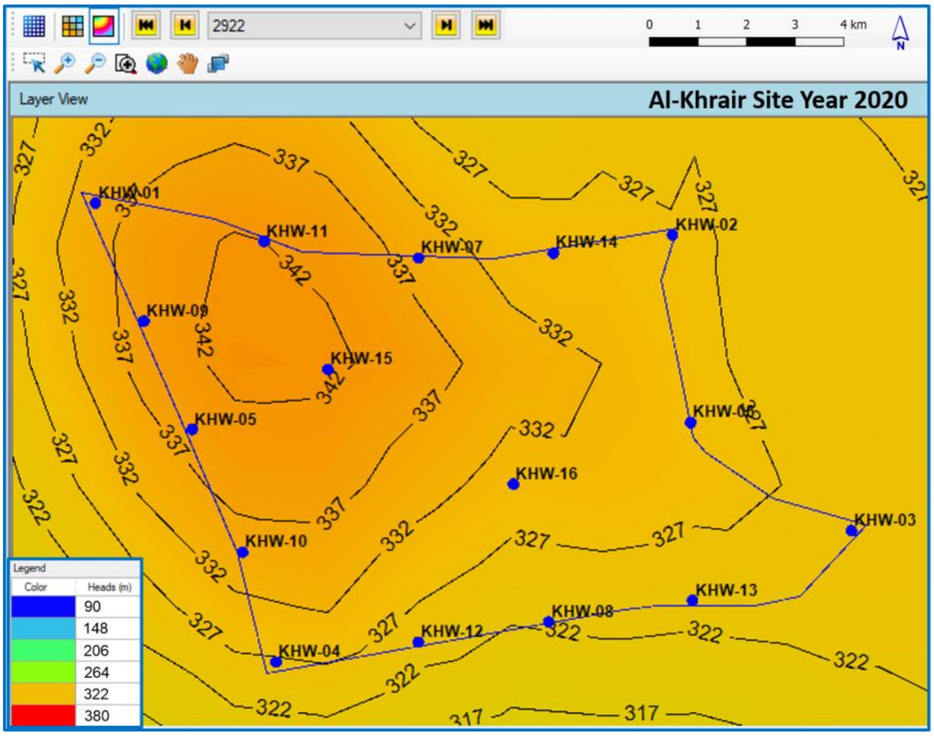


Figure 63: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site

b)



c)

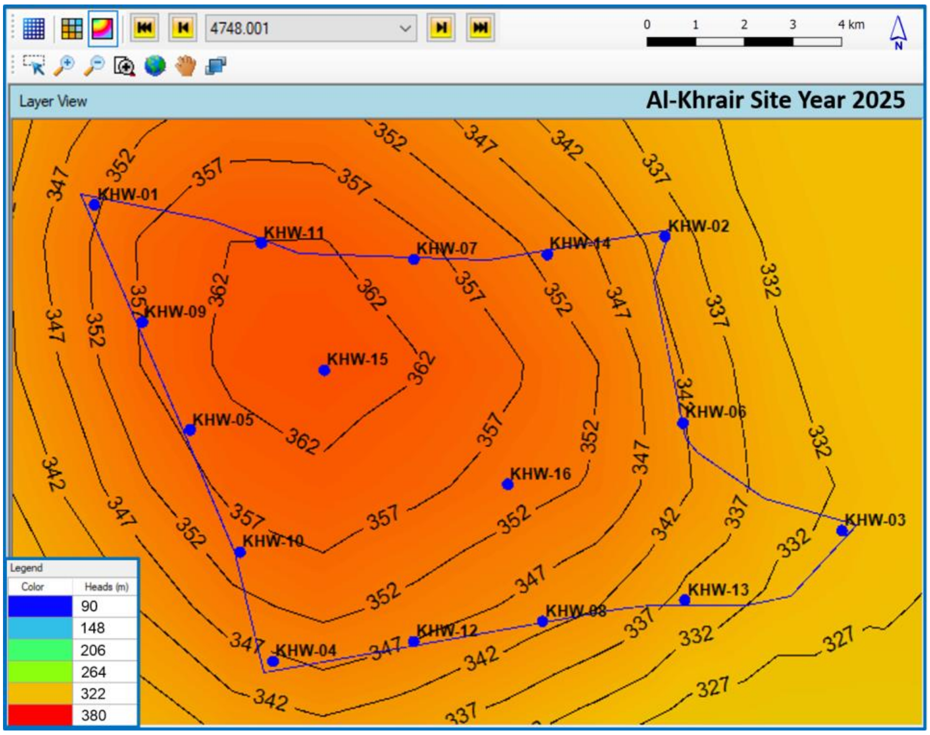


Figure 63: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

d)

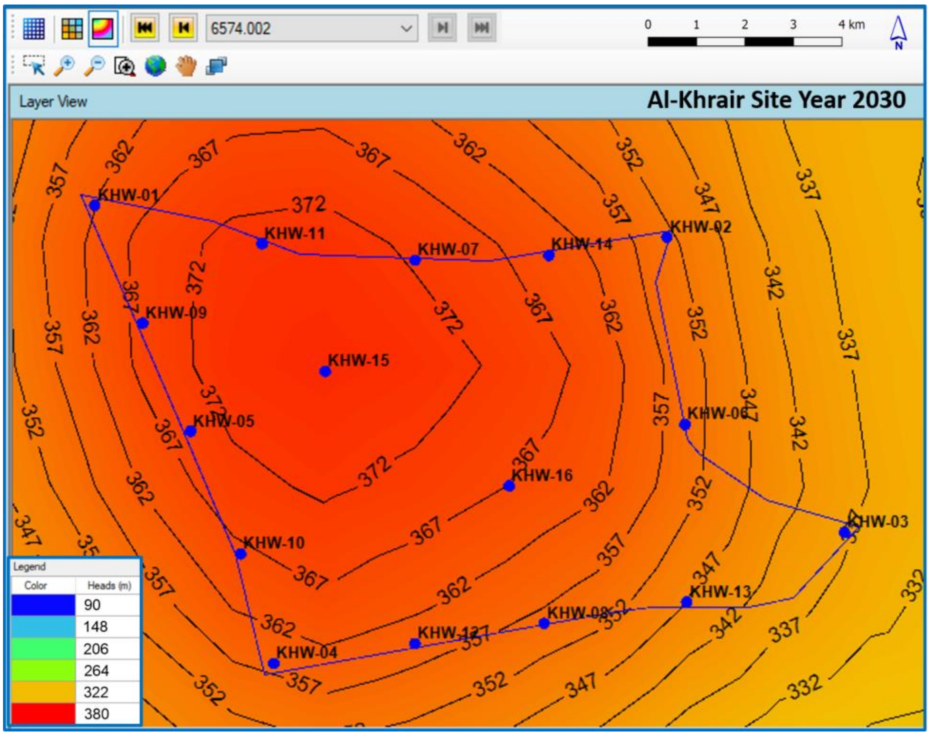


Figure 63: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

a)

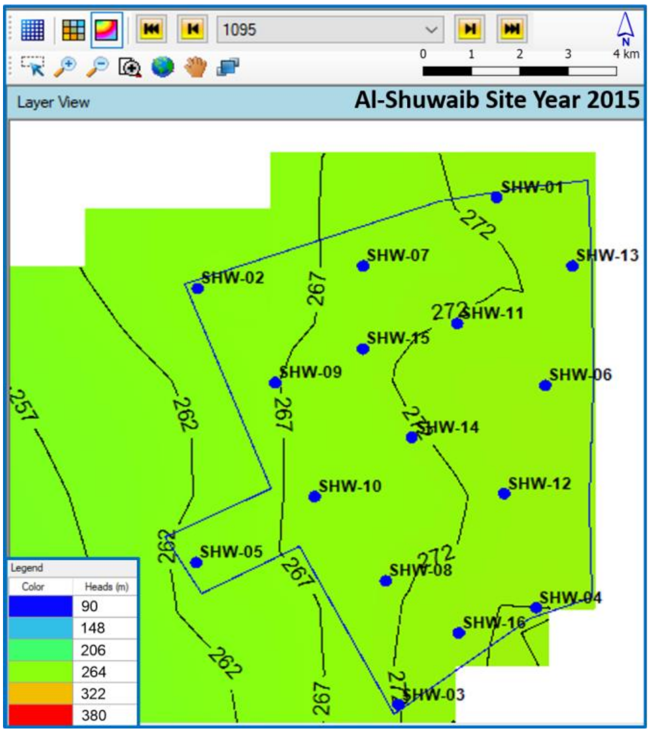
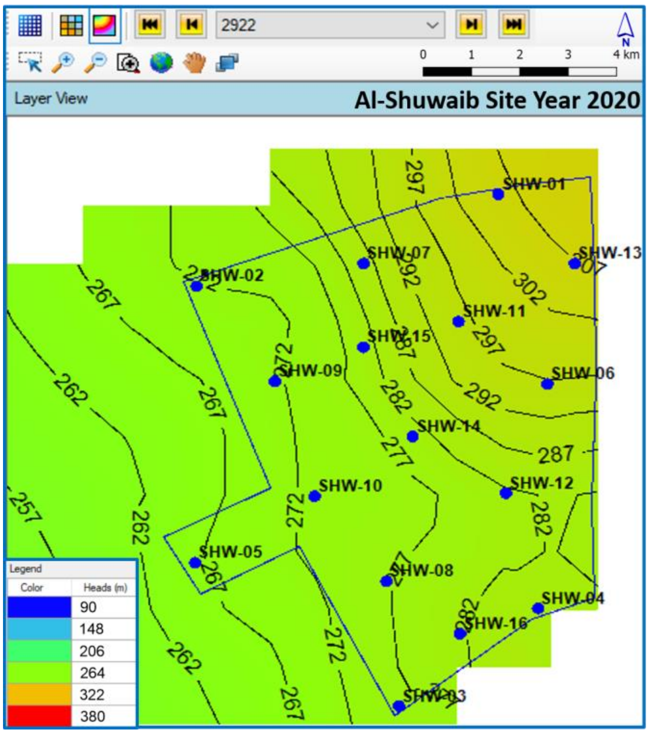


Figure 64: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site

b)



c)

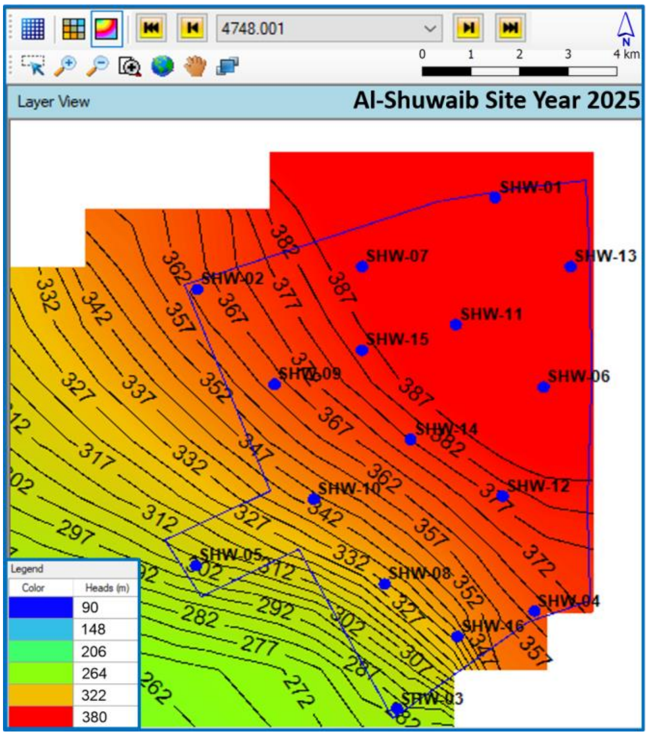


Figure 64: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

d)

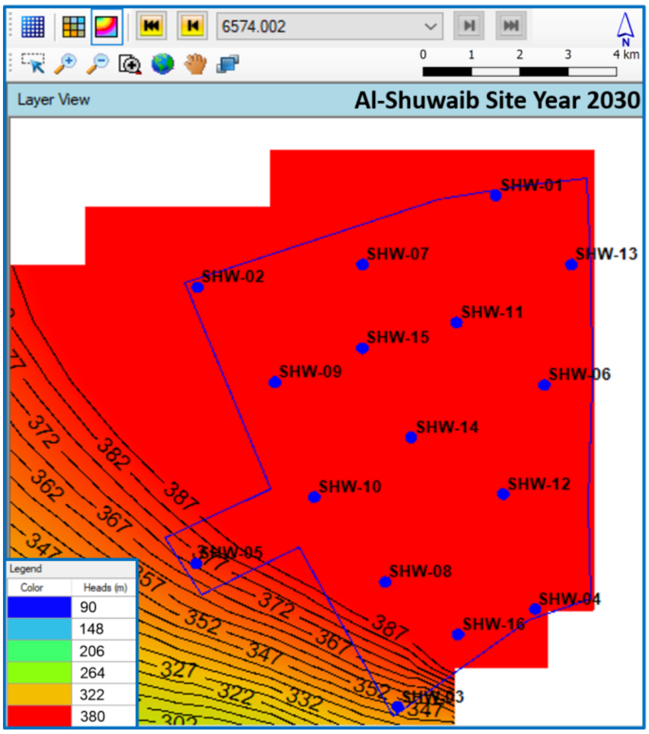


Figure 64: ASR scenario 4 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

From the above results, the hydraulic head in Al-Khrair site has increased from 307 m in 2015 at the west of the site to around 367 m in 2030 while the eastern part of the site has increased from 322 m in 2015 to around 356 m in 2030. An isolated reverse cone of depression has been developed around KHW-1 in 2015 and started to increase with time forming a bigger reverse cone of depression around KHW-11 and KHW-15 in 2030.

For Al-Shuwaib site, the hydraulic head has increased from 265 m in 2015 at the west of the site to hydraulic head exceeding 400 m in 2030 while the eastern part of the site has increased from 277 m in 2015 to hydraulic head exceeding 400 m in 2030.

6.2.6 ASR Scenario 5 (Recharge Rate 64,000 m^3/day)

In this scenario, the model was simulated with total water recharge rate of 64,000 m^3/day from year 2015 until 2030 through 8 injection wells (8,000 m^3/day per well) located at each selected site. The results of each site are presented in Figures 65 and 66.

a)

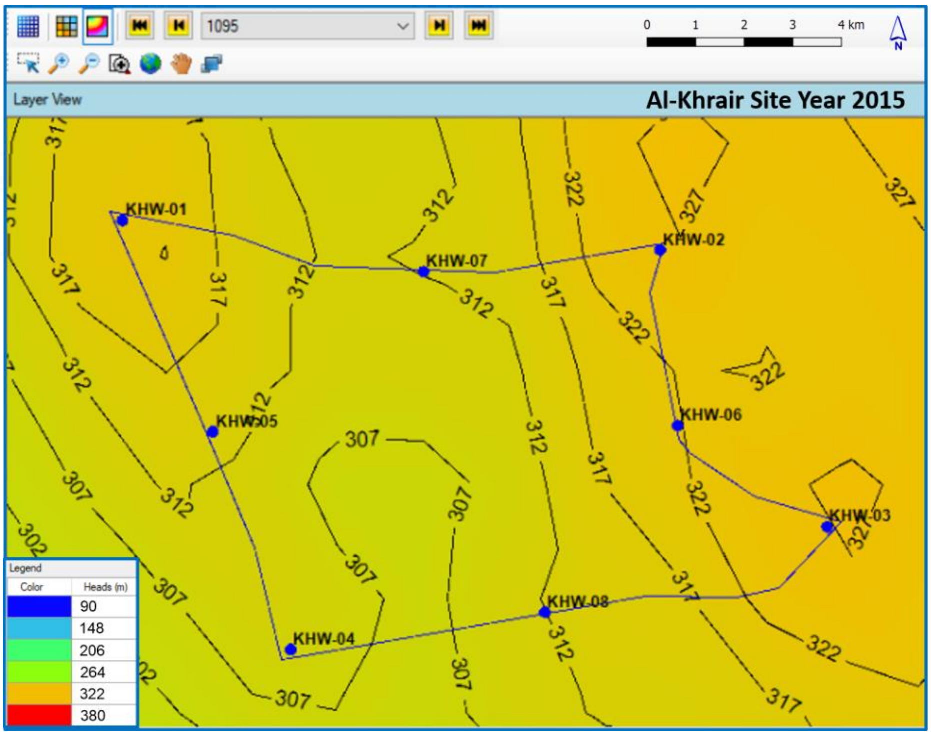
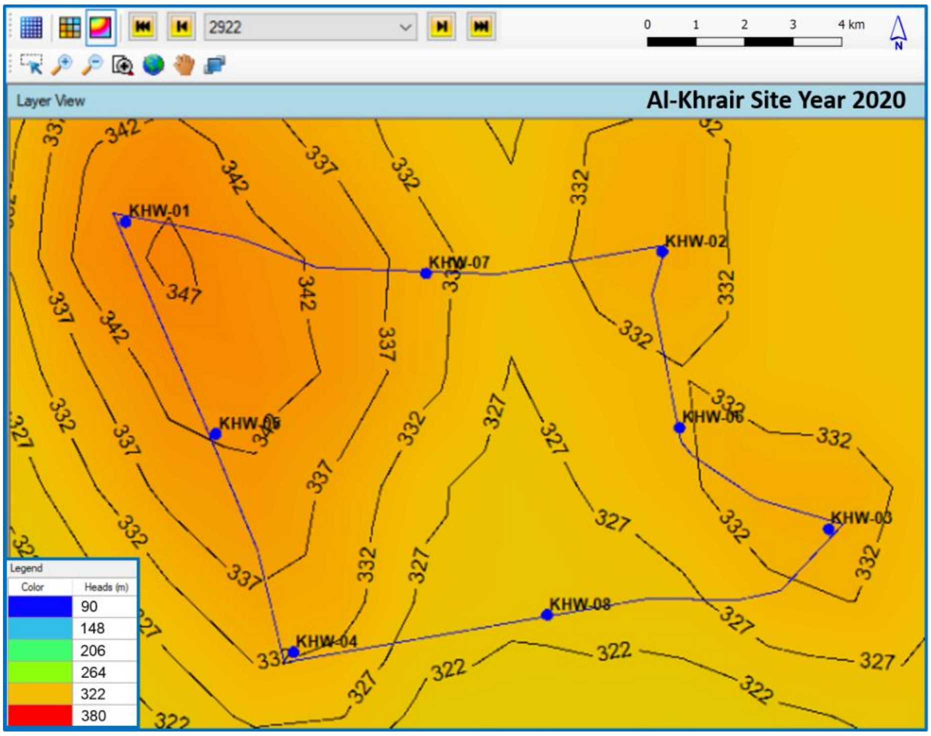


Figure 65: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site

b)



c)

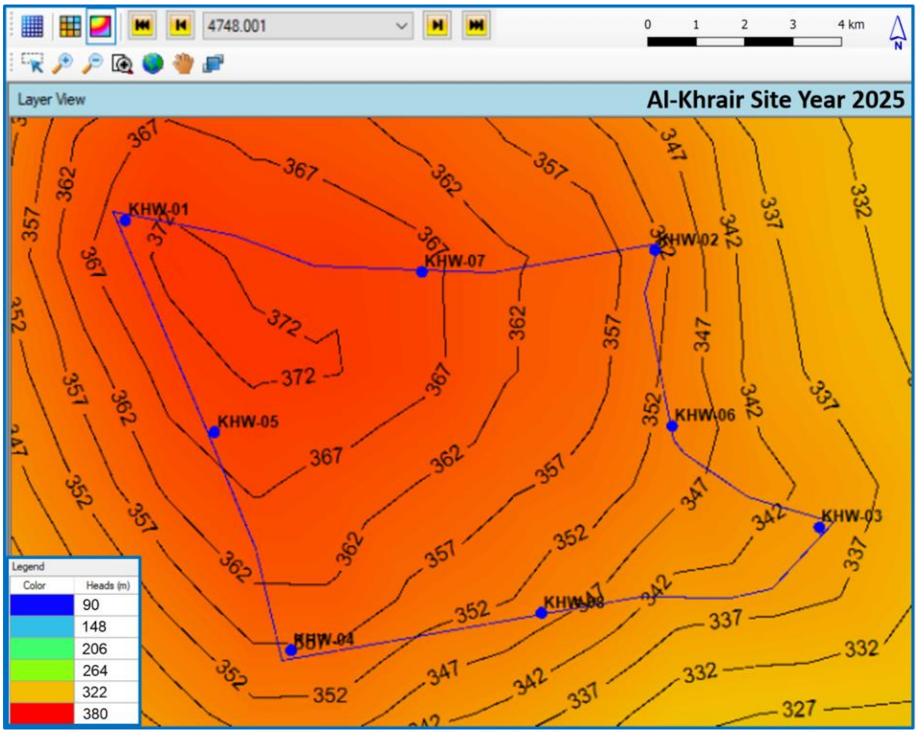


Figure 65: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

d)

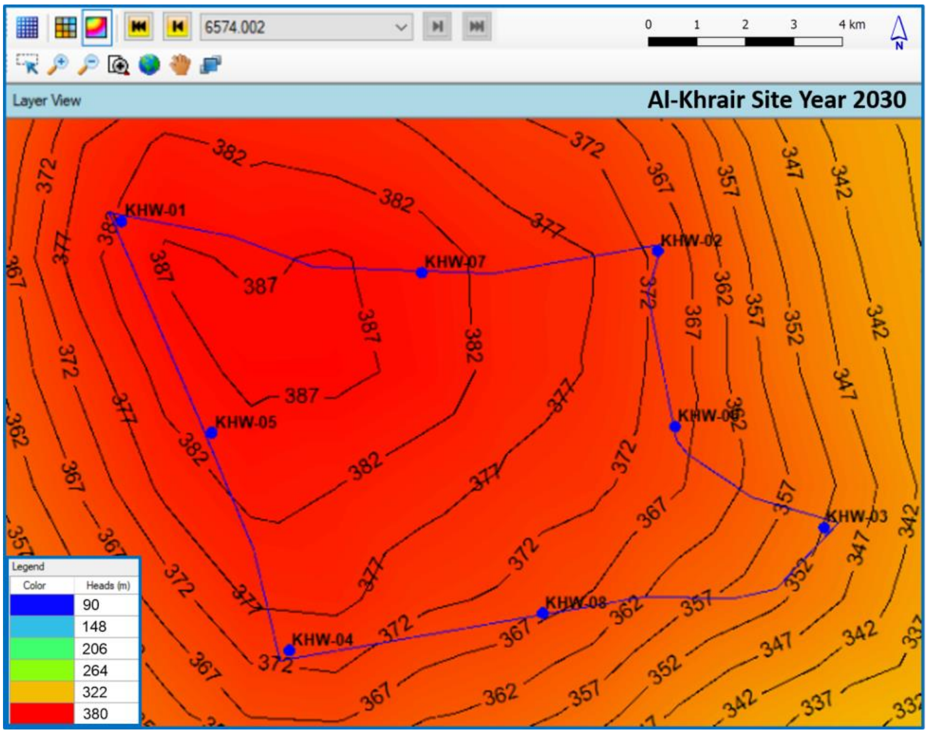


Figure 65: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Khrair site (Continued)

a)

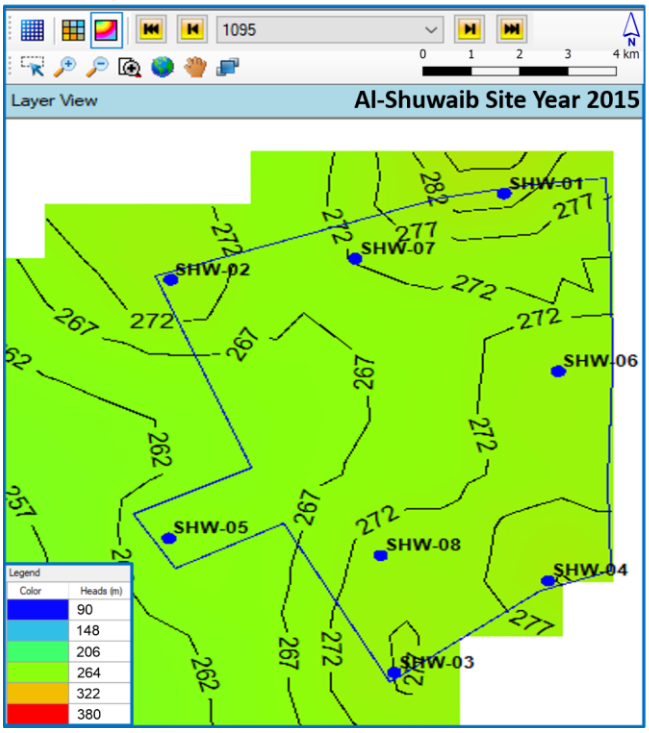
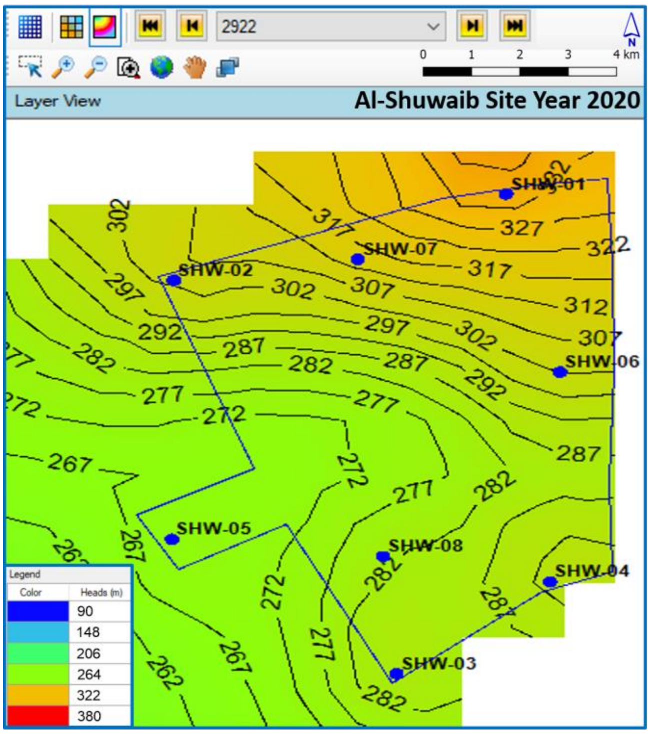


Figure 66: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site

b)



c)

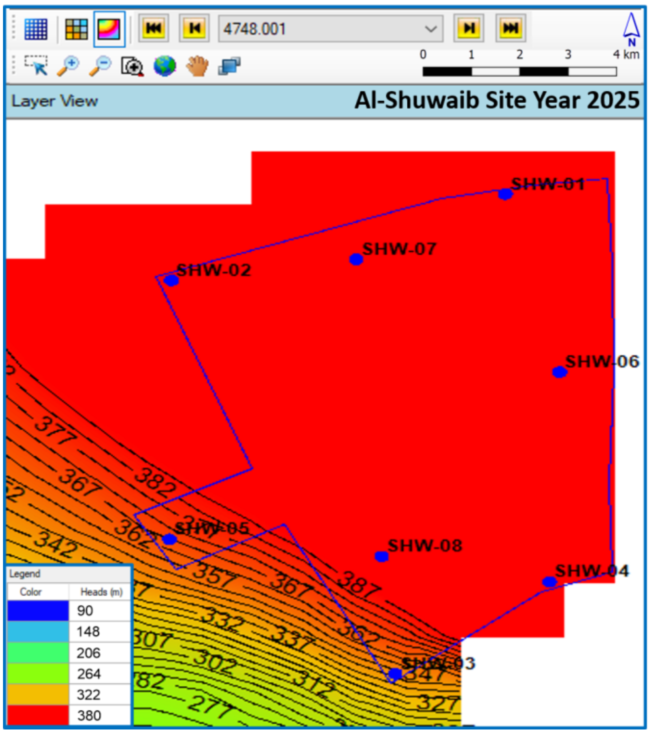


Figure 66: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

d)

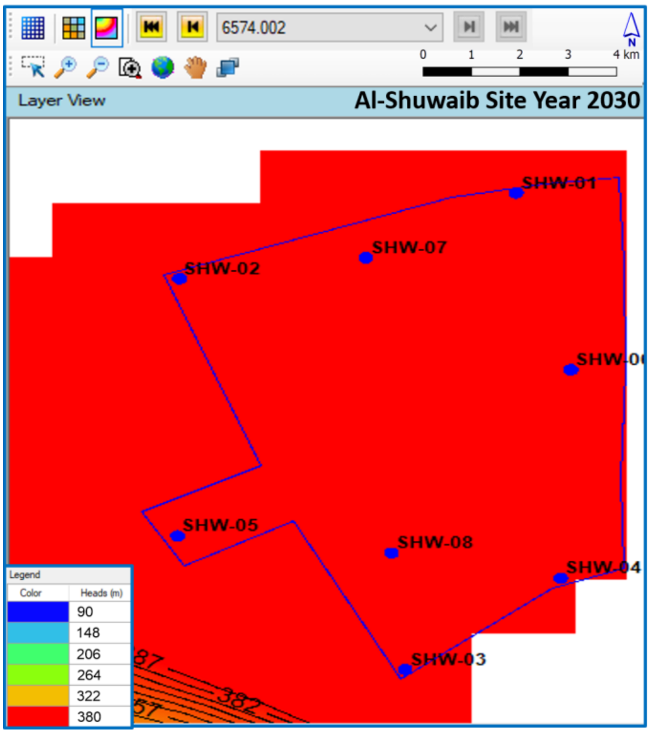


Figure 66: ASR scenario 5 simulated hydraulic heads for a) 2015, b) 2020, c) 2025, and d) 2030 in Al-Shuwaib site (Continued)

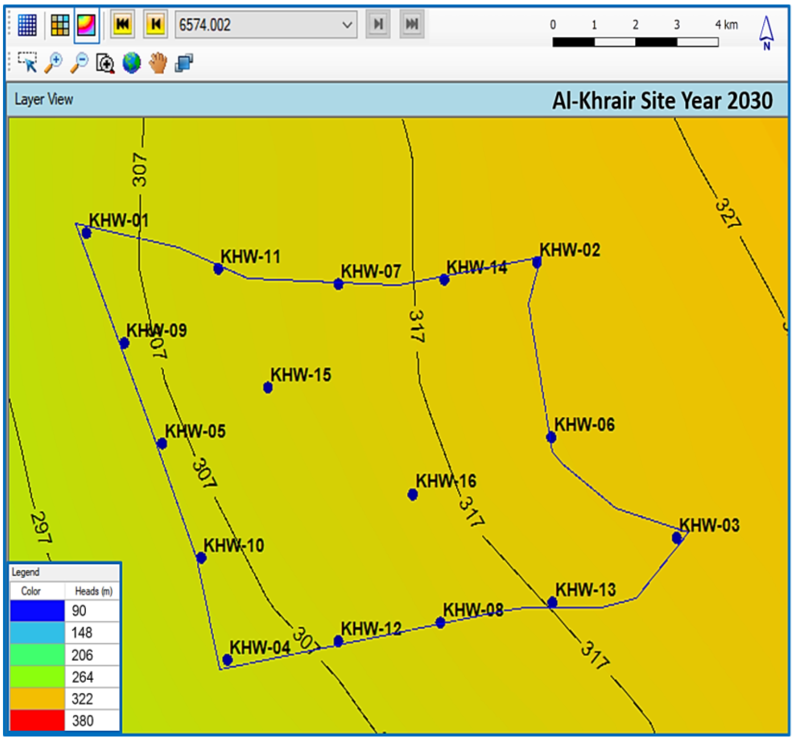
From the above results, the hydraulic heads in Al-Khrair site formed an isolated reverse cone of depression around injection wells KHW-01, KHW-02, KHW-03, and KHW-04 in 2015. 317 m at KHW-01, 327 m at KHW-02 and KHW-03, and 307 m at KHW-04 hydraulic heads were observed in 2015. These values increased in 2020 to 347 m at KHW-1, 332 m at KHW-02 and KHW-03, and 332 m at KHW-04. At the northwest of the site, reverse cone of depression developed towards KHW-01 with hydraulic head of 387 m in 2030.

For Al-Shuwaib site, hydraulic heads of 277 m was formed around SHW-01 to SHW-04 while the minimum hydraulic head is 262 m at SHW-05 in 2015. These values of hydraulic heads increased continuously until 2020 with hydraulic head of 382 m at SHW-01, 302 m at SHW-02, 282 m at SHW-03, and 292 m at SHW-04 while the minimum is 267 m at SHW-05. In 2025, most of the site has hydraulic heads exceeding 380 m except the southwest of the site near SHW-05 with hydraulic head of 362 m. In 2030, the hydraulic head exceeds 380 m in the whole site.

6.3 Comparison between ASR Scenarios

In order to find the most suitable site for an ASR project, a comparison of the simulated hydraulic head in 2030 at each site to examine the capability of each site to store the surplus of water which was estimated around 64,000 m^3/day. The comparison will help to identify which site is less sensitive to the significant increases in hydraulic heads and changes in groundwater flow behavior. Therefore, similar total recharge rates were compared at each site.

The hydraulic heads obtained at each site with total recharge rate of 16,000 m^3/day in 2030 is showing slight increase compared to 2015. Al-Khrair site hydraulic head contours seems more smooth and similar to the hydraulic heads in 2015 while in Al-Shuwaib site, the hydraulic heads are less smooth with slight increase at the southeast of the site as presented in Figure 67.



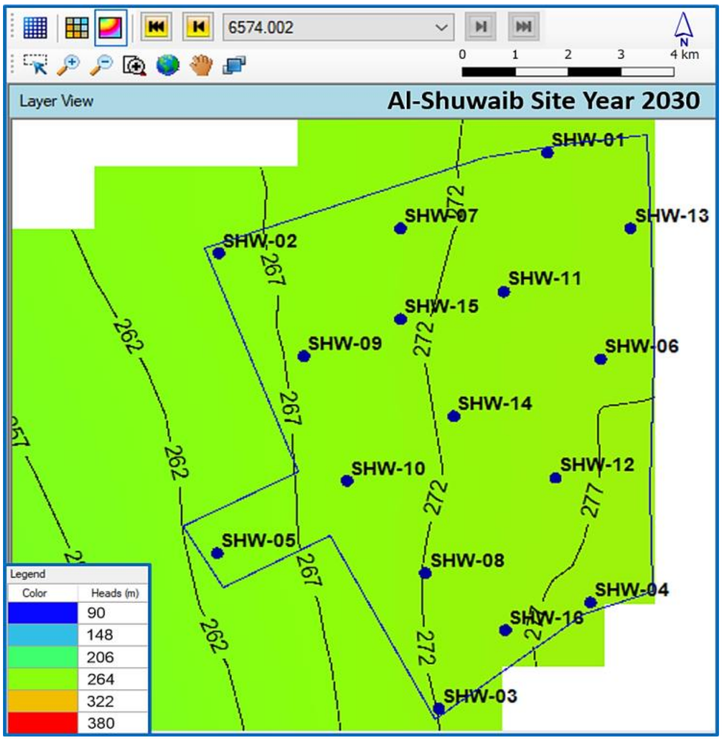
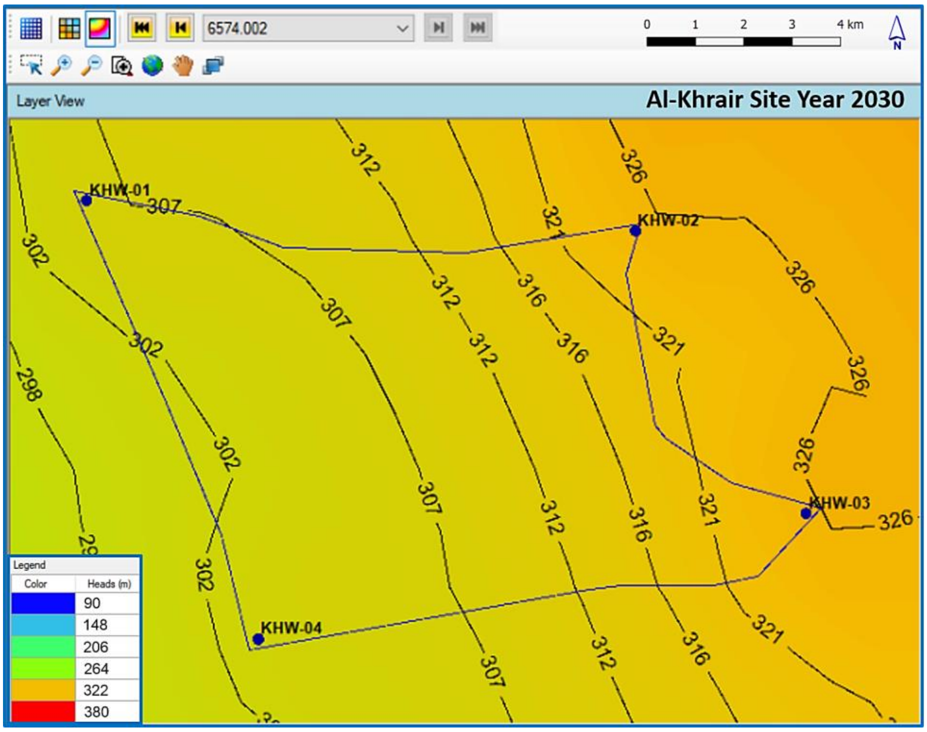


Figure 67: Simulated hydraulic heads in 2030 at each site with total recharge rate of 16,000 m^3/day

These results indicate the capability of both sites to be recharged by 16,000 m^3/day without significant changes in the groundwater behavior.

Two comparisons of total recharge 32,000 m^3/day were developed. Total recharge of 32,000 m^3/day was achieved by 8 injection wells with recharge rate of 4,000 m^3/day per well and also was achieved by 4 injection wells with recharge rate of 8,000 m^3/day per well. The hydraulic heads obtained from the 4 injection wells with recharge rate of 8,000 m^3/day at each site in 2030 is presented in Figure 68. The hydraulic heads in Al-Khrair site increased at the corners of the site at the location of the injection wells especially at the east and no significant changes in the groundwater flow or any reverse cone of depression noticed. For Al-Shuwaib site, the hydraulic heads seems disturbed in the middle of the site creating irregular trend. These results indicate the capability of Al-Khrair site to be recharged by total of 32,000 m^3/day without significant changes in the groundwater behavior or excessive head build-up. However, Al-Shuwaib site is considered to be capable to recharge the same amount but with less suitability than Al-Khrair site.



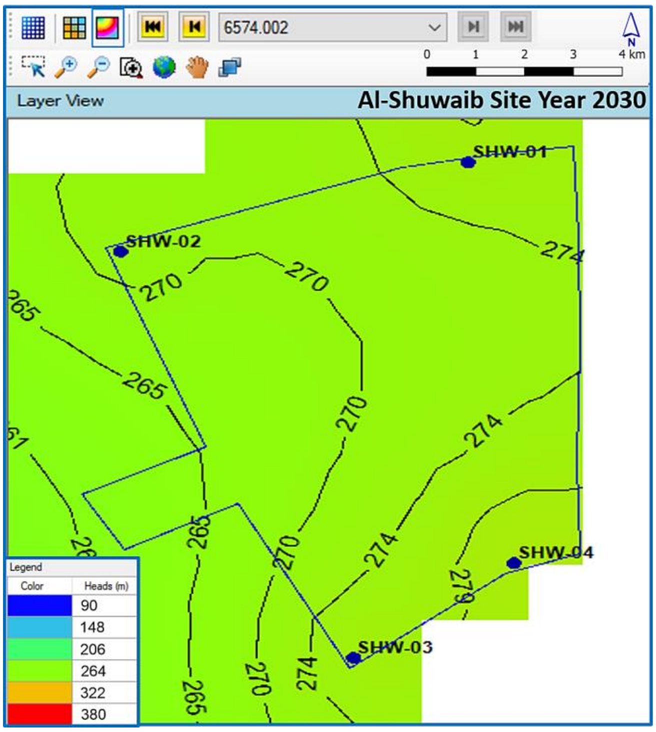


Figure 68: Simulated hydraulic heads in 2030 at each site with total recharge rate of 32,000 m^3/day using 4 injection wells

The hydraulic heads obtained from the 8 injection wells with recharge rate of 4,000 m^3/day at each site in 2030 is presented in Figure 69. The hydraulic heads in Al-Khrair site in 2030 shows a reverse cone of depression formed near to KHW-01 and KHW-07 at the northwest of the site. However, the hydraulic heads observed didn’t exceed the ground level while for Al-Shuwaib site, the hydraulic heads increased noticeably and exceeded the ground level. This total recharge rate is possible in Al-Shuwaib site until 2020 without an excessive head build-up as presented in Figure 62.

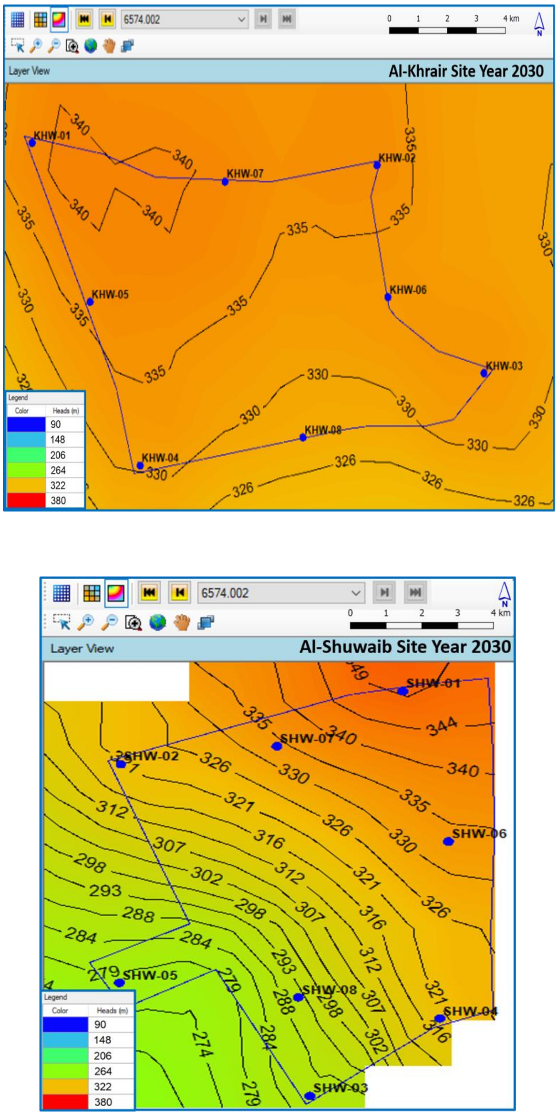
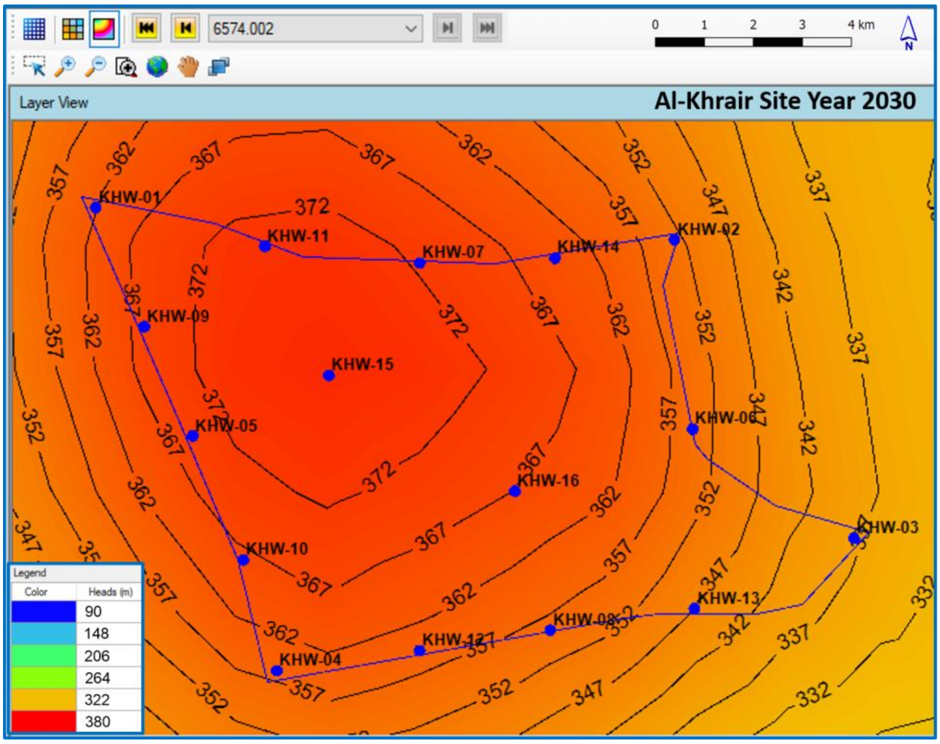


Figure 69: Simulated hydraulic heads in 2030 at each site with total recharge rate of 32,000 m^3/day using 8 injection wells

From Figures 68 and 69, the total recharge rate of 32,000 m^3/day has less influence on the hydraulic heads and groundwater flow behavior if achieved using 4 injection wells rather than 8 injection wells as the possible interference of hydraulic heads at each well is less. Both site can be recharged by 32,000 m^3/day if 4 injection wells are used but in case of 8 injection wells are used, Al-Khrair site is only applicable.

Similar to total recharge rate of 32,000 m^3/day, two comparisons of total recharge 64,000 m^3/day were developed. Total recharge of 64,000 m^3/day was achieved by 16 injection wells with recharge rate of 4,000 m^3/day per well and also was achieved by 8 injection wells with recharge rate of 8,000 m^3/day per well. The hydraulic heads obtained from the 16 injection wells with recharge rate of 4,000 m^3/day at each site in 2030 is presented in Figure 70.



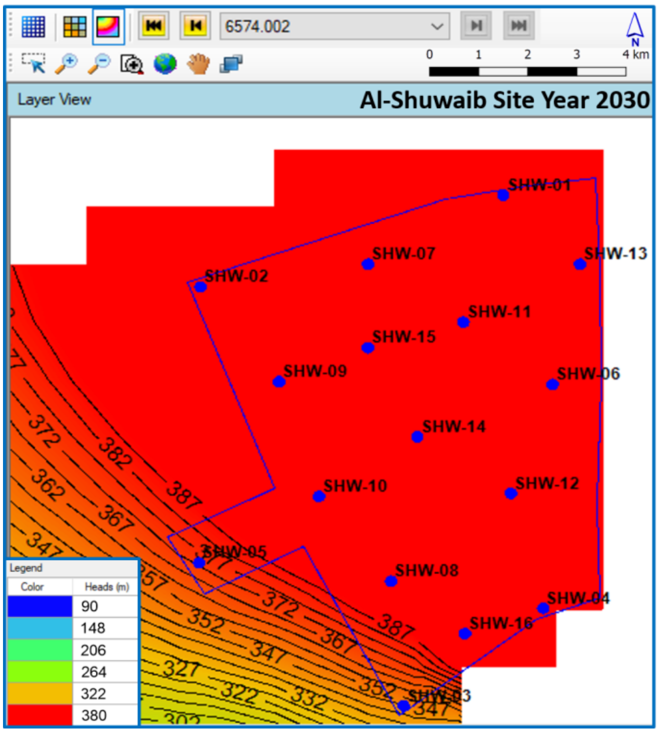


Figure 70: Simulated hydraulic heads in 2030 at each site with total recharge rate of 64,000 m^3/day using 16 injection wells

The hydraulic heads in Al-Khrair site in 2030 shows a huge reverse cone of depression developed around KHW-11 and KHW-15 at the northwest of the site with hydraulic heads exceeds the ground level after 2020 as presented in Figure 61. For Al-Shuwaib site, the hydraulic head increased significantly with excessive head buildup. This total recharge amount is possible in Al-Shuwaib site until 2015 without excessive head build-up as presented in Figure 64.

The hydraulic heads obtained from the 8 injection wells with recharge rate of 8,000 m^3/day at each site in 2030 is presented in Figure 71.

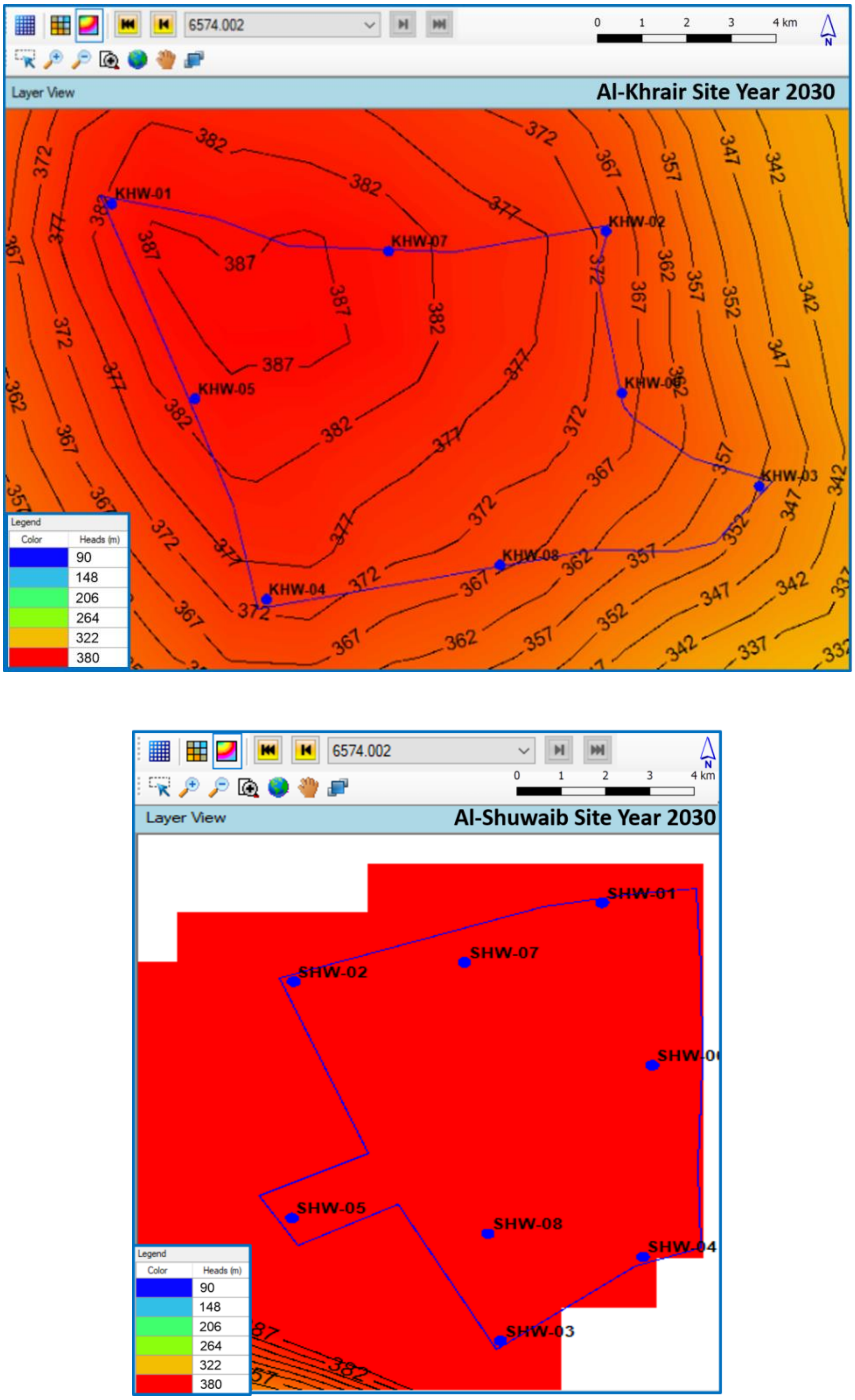


Figure 71: Simulated hydraulic head in 2030 with total recharge rate of 64,000 m^3/day using 8 injection wells

The hydraulic head in Al-Khrair site in 2030 shows a huge reverse cone of depression formed near to KHW-01 and KHW-07 at the northwest of the site with hydraulic heads exceed the ground level after 2020 as presented in Figure 63. For Al-Shuwaib site, the hydraulic head increased significantly with excessive head buildup. This total recharge amount is possible in Al-Shuwaib site until 2015 without excessive head buildup as presented in Figure 66.

A summary of the recharge rate with it is possible implementation in the sites are listed in Table 29.

Table 29: Summary of the recharge rate with it is possible implementation in the sites

Number of Wells	**Recharge Rate (m^3/day)**	**Total Recharge Rate (m^3/day)**	**Al-Khrair Site**	**Al-Shuwaib Site**
16	1,000	16,000	Applicable until 2030	Applicable until 2030
4	8,000	32,000	Applicable until 2030	Applicable until 2020
8	4,000	32,000	Applicable until 2030	Applicable until 2030
8	8,000	32,000	Applicable until 2020	Applicable until 2015
16	4,000	64,000	Applicable until 2020	Applicable until 2015

6.4 Comparison of the Selected Sites with the Potential ASR Sites in the Study Area from Different Authors

Several authors studied the suitability for groundwater aquifer in Al-Ain region in the last few years (Hutchinson, 1998; Dawoud, 2013; Sadhasivam and Mohamed, 2018). Each author depend on different criteria for the evaluation of the future ASR project. For instance, Environment Agency - Abu Dhabi (Dawoud, 2013) used some hydrogeological criteria such as thickness of the aquifer, thickness of the unsaturated zone, aquifer confinement, quality of native groundwater, aquifer transmissivity and storativity, hydraulic gradient and presence of third party using the aquifer. In addition, few other criteria such as distance to closest border or coastline, infrastructure, environmental aspects and land development. Dawoud (2013) assessment of the ASR project was done by discarding the locations that will not achieve three or more suitability criteria as presented in Figure 72.

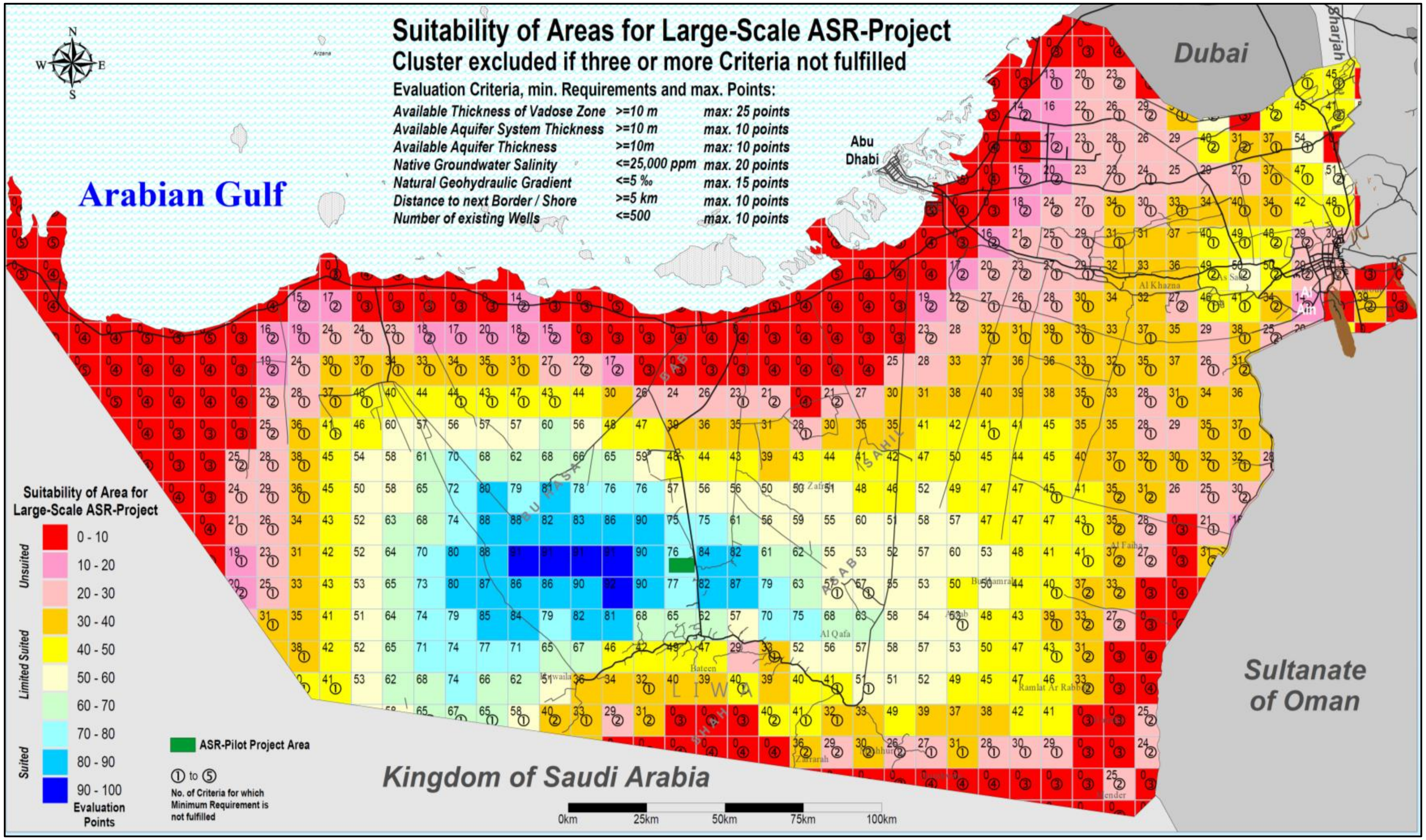


Figure 72: Suitability map of large scale ASR project in Abu Dhabi Emirates (Dawoud, 2013)

Another study of assessment of ASR project in Abu Dhabi Emirate was also done recently by Sadhasivam and Mohamed (2018). In this investigation, hydrogeological criteria as well as performance of each site in terms of rate of injection, total volume of injection, recovery efficiency, radius of influence and type of cone were examined in order to find the most suitable location in Abu Dhabi Emirates including the study area. Each author came out with three suitable sites for an ASR project in the study area. Figure 73 presents the suitable sites for ASR project by each author according to their suitability ranking as well as the three suitable sites simulated in this study (Al-Khrair, Al-Shuwaib, and Al-Bateen sites).

The suitable sites in this study mainly located east of the study area. Al-Shuwaib site is located approximately near to Site 1 and 3 by (Sadhasivam and Mohamed, 2018) and site 2 and 3 (Dawoud, 2013). Sites 1 and 2 Sadhasivam and Mohamed (2018), are located at Sweihan site west of the study area while Site 1 by Dawoud (2013), is located in Al-Saad site which is near to the excluded Site (Al-Bateen). According to the ASR Sites selection criteria implemented in this thesis, Sweihan site was ranked number 11 and 13 while Al-Saad site was ranked 18 and 8 in the first and second site evaluation, respectively (Tables 12 and 20).

Figure 73: Suitable sites for ASR project by each author as well as the three suitable sites in this study (Dawoud, 2017; Sadhasivam and Mohamed, 2018)

Sweihan site was assigned a low score/ranking due to several factors such as the salinity of aquifer and the continues withdrawal of groundwater for agriculture activities which depleted the aquifer (Al-Alawi, 2014; EAD, 2018). Al-Saad Site was assigned a low score/ranking due to the same reason at Sweihan site (Al Badi, 2003).

It was noticed that the selected the suitable sites for an ASR project based mainly on the available surface storage tanks/water facilities located nearby the selected sites presented in Figures 1 and 4. In addition, most of the selected sites were located east of the study area.

In the last decade, the groundwater level in Al-Khrair and Al-Shuwaib sites are located within the stable zone according to the groundwater level changes map developed by EAD (2018), shown in Figure 74. ASR sites 1 and 3 (Sadhasivam and Mohamed, 2018) and site 2 (Dawoud, 2013) are located close to Al-Hayer area which is showing continuous decline in groundwater level in the last decade.

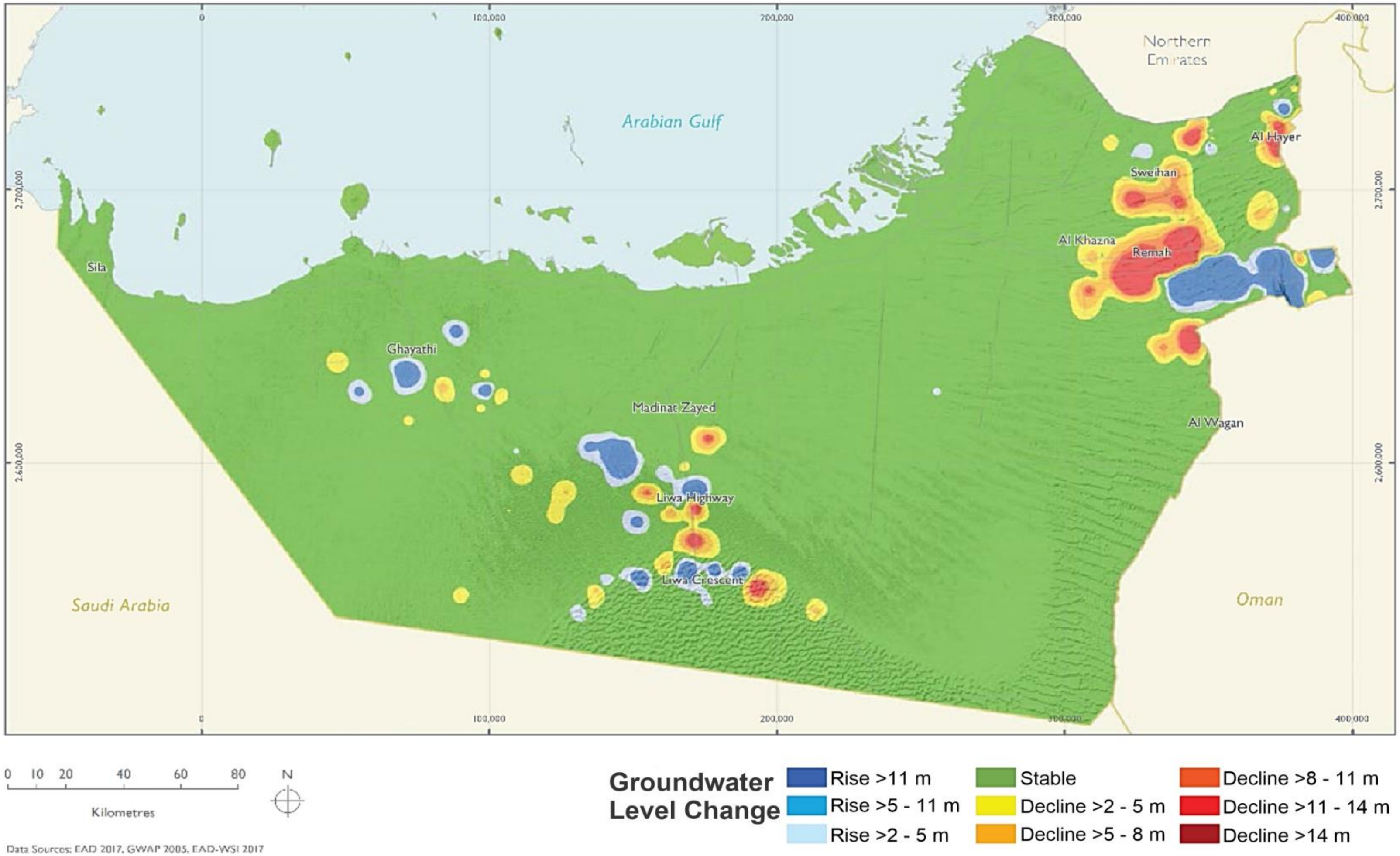


Figure 74: Groundwater level change 2005-2017 (EAD, 2018)

6.5 Ranking of the Selected Sites

The selected sites for an ASR projects are Al-Khrair area, Al-Shuwaib area, and Al-Bateen Area. Each site has its own hydrogeological characteristics and recharge capacity limit according to the simulated hydraulic heads in the model period which started in 2013 and ended in 2030. Further, Al-Bateen site was excluded from the additional recharge scenarios due to the limited recharge capacity which was estimated around 2,000 m^3/day. The additional assessment of Al-Khrair and Al-Shuwaib sites was implemented to identity the best site for ASR system that can be recharged with huge amount of water without changing in the groundwater behavior or excessive head buildup.

Additional criteria can be applied to the selected sites of Al-Khrair and Al-Shuwaib to identify the most suitable site of an ASR system. The additional criteria are explained as follow;

- *Distance to the Nearest border*

Al-Khrair site is located to the east of the study area within Al-Jaww plain. The nearest border to the site is Sultanate of Oman borders which is approximately 12 km away from the site. Al-Shuwaib site is located north of the study is around 10 km to Sharjah Emirate and 8 km to Sultanate of Oman borders on the east. Figure 75 presents the location of the two sites. Al-Khrair site is located at more appropriate location than Al-Shuwaib site.

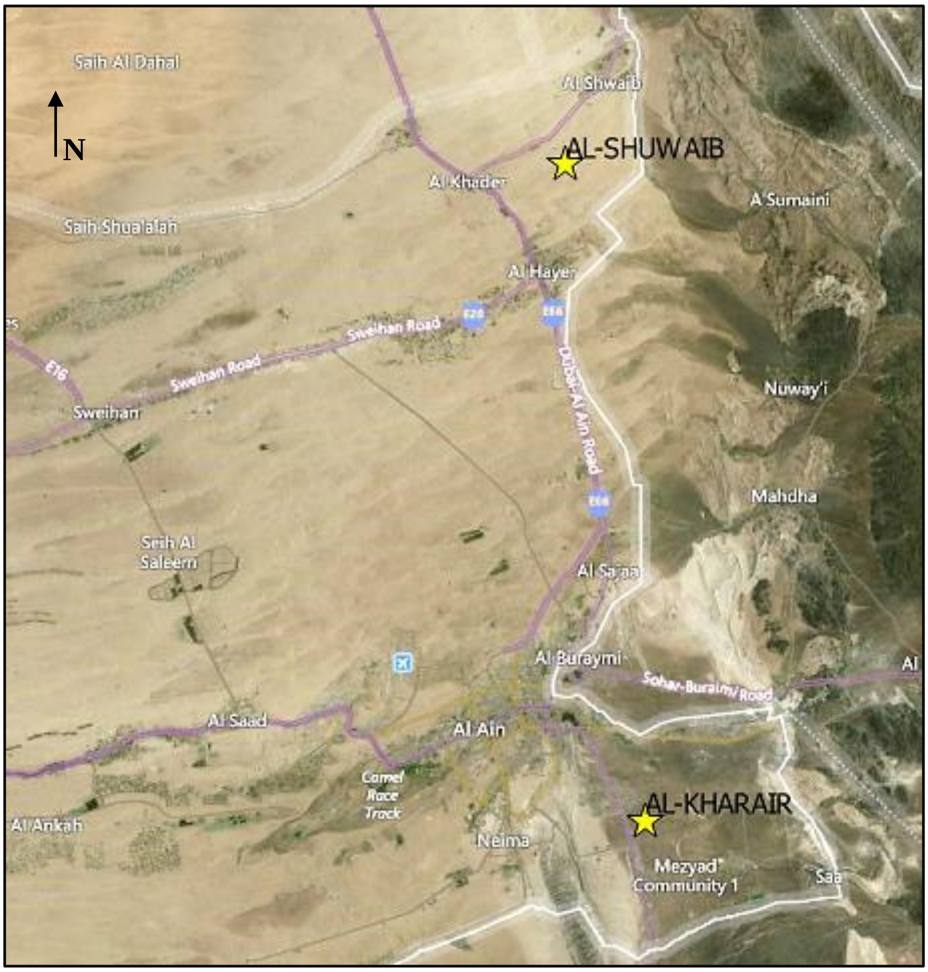


Figure 75: Location of the selected sites and the nearest borders

➢ *Depth to the Groundwater table*

Depth to the groundwater table represents the depth from ground surface to the groundwater table. According to the obtained borehole data, the groundwater table for Al-Khrair site was encountered at depths around 40 m below ground level while for Al-Shuwaib site the groundwater table was encountered at depths around 20 m below ground level. These depths are expected to be shallower after water recharge from injection wells. Therefore, it is preferable to have deeper groundwater table as it has less chance for contaminating the aquifer from nearby surface sources (Bartzas et al., 2015; Waller, 2016). Thus, Al-Khrair site is more suitable than Al-Shuwaib site.

- *Distance to the surface water storage or Pumping station*

Within the study area, several exiting pumping station facilities are located and owned by TRANSCO as presented in Figure 76.

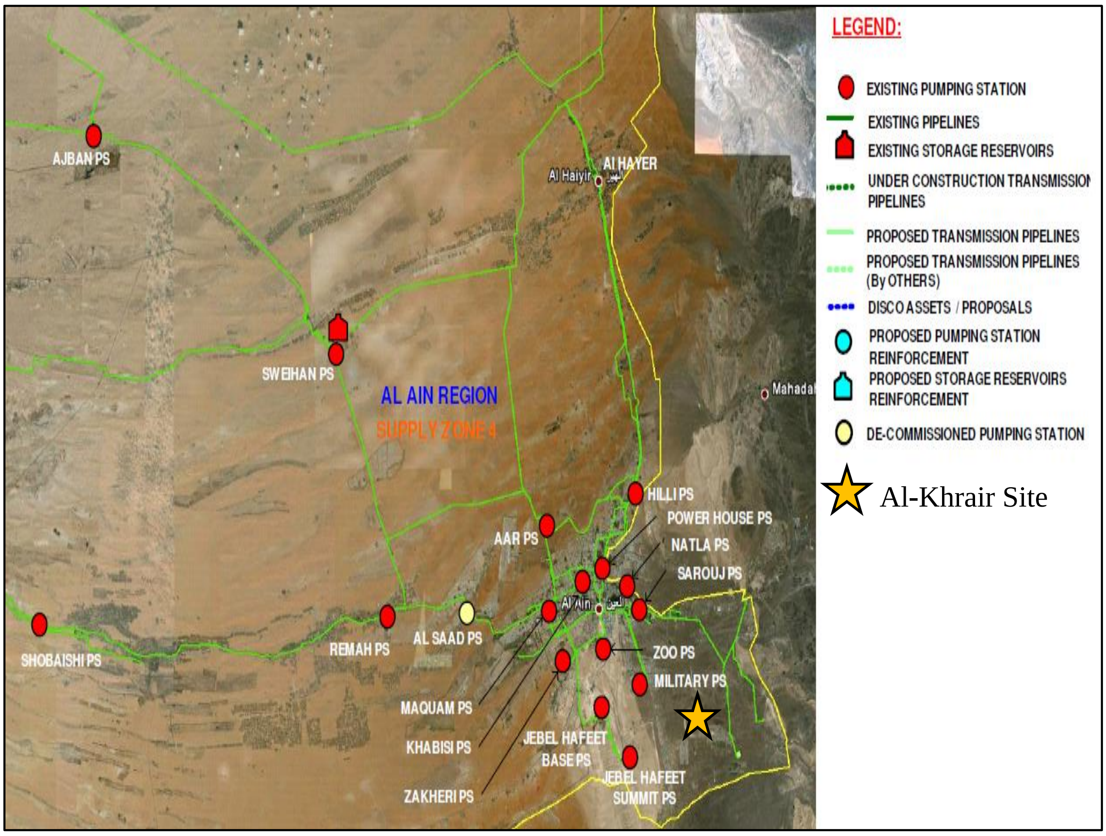


Figure 76: Pumping station / supply zones in the vicinity of Al-Khrair site (TRANSCO, 2013)

Several pumping stations are located in the vicinity of Al-Khrair site while for Al-Shuwaib site the only nearby pumping station is located at Al-Hayer area 19 km away as presented in Figure 77.

Figure 77: Nearest pumping station / supply zones to Al-Shuwaib site

Further to the additional assessment implemented on Al-Khrair and Al-Shuwaib sites to choose the most suitable site for aquifer storage and recovery project. Accordingly, the selected sites are ranked as listed in Table 30.

Table 30: Ranking of the selected sites for ASR project

Rank	**Site**	**Recharge capacity**	**Number of years to be recharged starting from 2013**
1	Al-Khrair	64,000 m^3/day	7
2	Al-Shuwaib	64,000 m^3/day	2
3	Al-Bateen	2,000 m^3/day	17

Furthermore, geophysical investigation using gravity method has been carried out in Al-Jaww plain (Ali et al., 2008) where Al-Khrair site is proposed has indicated that the area revealed a major syncline indicated by a strong negative anomaly (low gravity) as well as a series of anticlines as shown in Figure 78. This confirms the perquisite stated by Maliva et al., (2007), for achieving a useful storage of water the ASR system must have and aquifer with lateral boundaries (like the wall of the tank) which will act as the wall of the tank as long as there is not leakage from the storage zone (Maliva et al., 2007).

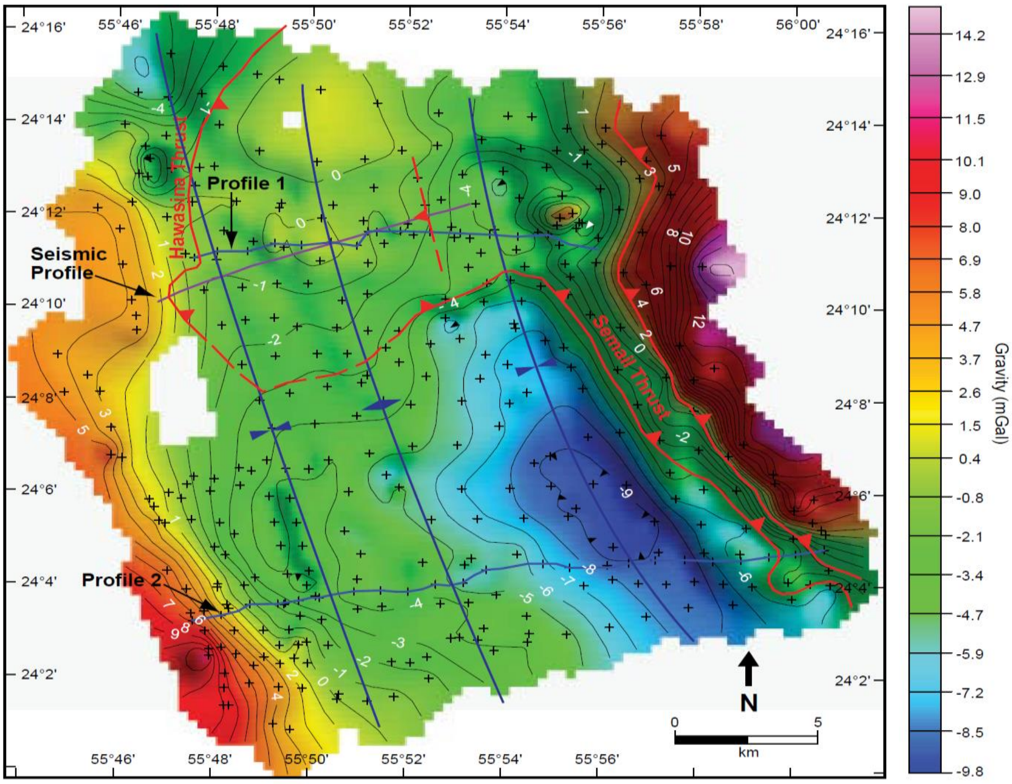


Figure 78: Geophysical gravity map conducted at Al-Jaww Plain revealing the geological structures in the area (Ali et al., 2008)

Thus, Al-Khrair site has a good potential site to store the water in the bowl-shape structure (syncline). In addition, there are big similarities between Al-Khrair site and the currently implemented ASR project in Liwa area, Abu Dhabi Emirate in terms of the existing natural groundwater with low salinity and the good extension of the permeable geological layers as well as aquifer thickness and the sufficient depth to the groundwater table (Dawoud, 2014).

Chapter 7: Conclusions and Recommendations

The study area is Al-Ain region (Al-Ain Basin) which is located at the eastern part of Abu Dhabi Emirate, UAE. The rapid development and the continuously growing of the population resulted in increasing of the water demands. The population of the Abu Dhabi Emirate has increased significantly compared to early 1960's. Furthermore, the desalination capacity has increased significantly in the last decades which reflect the increase in water demand.

The need for an alternative approach to manage the water supply demand and provide uninterrupted freshwater supply is a major concern in the Abu Dhabi Emirate. MAR is considered to have the potential to be a major contributor for water supply in semi-arid and arid countries where groundwater is over-exploited or saline. One method to achieve this storage capacity and overcome the increasing water demands is ASR 'aquifer storage and recharge' by injecting the aquifers with the excess freshwater produced by the desalination plants into strategic underground aquifers for future use.

Three previous ASR pilot projects of artificial recharge have been studied in the UAE, specifically in Nizwa, Sharjah Emirate, in the western region 'Liwa' of Abu Dhabi Emirate and in Al- Ain region. Only the ASR project in Liwa was successfully constructed and started the large scale water infiltration in 2015 (Stuyfzand et al., 2017)

ASR site selection should be studied and planned carefully in order to minimize the potential problems and maximize the performance. The study must include multiple planning factors in the assessment of the ASR site feasibility and an extensive data coupled with strong numerical models to reduce the uncertainties of the aquifer properties as well as knowledge of the hydrogeological characteristics in order to accurately select the best site for Aquifer storage and recovery. A modified hydrogeological and infrastructural criteria and its suitability assessment was implemented on 21 selected site for assessing the suitable sites for ASR system and disqualifying the sites that doesn’t match the suitability assessment. Accordingly, 3 selected sites were chosen for the assessment namely, Al-Khrair site, Al-Shuwaib site, and Al-Bateen site.

The selected sites were evaluated using the Visual MODFLOW Flex 2015.1 Software (Visual MODFLOW Flex groundwater modeling software) utilizing the finite-difference for the best sites for ASR system and to identify the site’s suitability for the implementation of ASR project. It was modeled that the surficial aquifer layer (unconfined and highly productive quaternary alluvium) and the upper Fars Formation is conceptualized as a one layer overlying the lower Fars Formation which is considered as impermeable layer. Three types of boundary conditions were used in the study model, namely no flow boundary, constant head boundary, and specified flux boundary.

Initially, 4 scenarios of water recharge were simulated. Based on the scenarios results, Al-Bateen site was excluded from this assessment due to it is excessive head build-up which limits water recharge to around 2,000 m^3/day. Although, this site is near to one of the Pumping stations/ surface storage tanks located in the vicinity of the area. A further assessment for the most suitable location for an ASR project between Al-Shuwaib and Al-Khrair sites only was implemented due to their ability to be recharged with 8,000 m^3/day. This recharge rate is almost similar to the excess treated wastewater daily discharged to the environment in Al-Ain region (Dawoud, 2017), 8 times greater than the recharge rate simulated previously in the study area (Hutchinson, 1998) and 2,000 m^3 more than the recharge rate simulated in Liwa, Abu Dhabi, UAE.

The additional assessment aimed to recharge Al-Shuwaib and Al-Khrair sites with the 23 MCM surplus from desalination plants in Abu Dhabi Emirate (Klingbeil, 2012). This assessment was started with close spaced injection wells (around 1,200 m away from each other) but as a result of the excessive rise in hydraulic head, a new distribution of injection wells was assigned to the site with wider space (to avoid the overlap and interference of the reverse cone of depression developed at each well. The wide space injection wells has distance of more than 1,200 m.

The new injection wells distribution was considered in the further assessment of the Al-Khrair and Al-Shuwaib sites. The aim was to examine which one of the sites can be recharge with the surplus desalinated water produced in Abu Dhabi Emirate that was estimated around 64,000 m^3/day. Thus, five (05) new ASR scenarios were developed with three main water recharges of 16,000 m^3/day, 32,000 m^3/day, and 64,000 m^3/day.

Based on the additional assessment results, it was found that Al-Khrair site can be recharged with 64,000 m^3/day for 7 years continuously before changing the behavior of the groundwater flow and develop excessive head build-up while for Al-Shuwaib site, it is possible to be recharged by 64,000 m^3/day for only 2 years.

The selected sites were also compared to the ASR sites proposed by (Sadhasivam and Mohamed, 2018) and (Dawoud, 2013) and it was found that Al-Shuwaib site is near to their proposed sites. It was also noticed that their proposed sites are in the vicinity of surface storage tanks. In addition, most of the sites are located east of the study area.

An additional criteria applied to the selected sites of Al-Khrair and Al-Shuwaib to identify the most suitable site of an ASR system in terms of closeness to water source, depth to water table, and thickness of the vadose zone. Accordingly, the most suitable site for an ASR project is Al-Khrair site followed by Al-Shuwaib site.

Al-Khrair site has a good potential site to store the water in the bowl-shape structure (syncline) revealed by the geophysical investigation carried out in Al-Jaww plain (Ali et al., 2008). In addition, there are big similarities between Al-Khrair site and the currently implemented ASR project in Liwa, Abu Dhabi Emirate in terms of the existing natural groundwater with low salinity and the good extension of the permeable geological layers as well as aquifer thickness and the sufficient depth to the groundwater table (Dawoud, 2014).

One of the limitations was the aquifers characterized by low to moderate hydraulic conductivity may result in high induced water levels or pressure which may result in surface flooding or loss of injected water through seepage to surface. This was encountered when the selected sites were injected with huge quantity of water. As well as the hidden geological structures such as faults which needs additional investigation using geophysical methods to reveal that the proposed site is not located on a fault which may result in seepage of the stored water.

Finally, it is recommended to carry out an extensive feasibility study in Al-Ain region including wide studies using computer models and geophysical investigations to find the optimum site of ASR project that will enhance water management in the Eastern District and build a back-up reservoir to face any potential threats of shortage or any interruptions in the freshwater supply.

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